Specialized Power-Electronic Apparatus for Harnessing Electrical Power from Kinetic Hydropower Plants

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Abstract

This thesis introduces a power electronic interface for a kinetic hydropower generation platform that enables extraction of electric power from a free-flowing water source such as a river or a stream. Water currents are of fluctuating nature and hence, a power interface is required to provide regulated voltage for the load from this resource.

The implemented system transfers power from a high-frequency permanent magnet synchronous generator (PMSG) to a 60-Hz load. Special configurations and control techniques were developed to cater for the long distance between the generator and the power interface; and also to address the wide range of the PMSG frequency and voltage variations. Simulation-based analysis was used for designing the components and validating the devised control strategies prior to construction. The proposed power-electronic interface was constructed and tested in the laboratory as well as in the field. These tests confirmed acceptable performance of the constructed power interface.

The thesis also introduces two feasible methods for controlling a hydrokinetic plant to supply islanded loads or to deliver the maximum power available from the turbine-generator to the utility network. Application of multiple turbines in a kinetic farm was also investigated, and different approaches to controlling hydrokinetic turbines in such a configuration were developed. Analysis was conducted using detailed simulation models on an electromagnetic transients (EMT) simulation program.
Acknowledgments

The development of a hydrokinetic research platform was an initiative proposed by Prof. Eric Bibeau from the University of Manitoba, and was supported by the department of emerging energy technologies at Manitoba Hydro. The research platform required a power interface to supply standard loads, and thus Prof. Ani Gole accepted to lead the efforts to develop the power interface.

Prof. Gole and Prof. Bibeau observed several aspects of this technology as research potential topics. With Prof. Gole’s vision, the foundations of this thesis were formed to investigate hydrokinetic power generation from the electrical system perspective.

This project was funded by the National Science and Engineering Council of Canada (NSERC) and was sponsored by Manitoba Hydro the Manitoba HVDC Research Centre Inc. The construction and commissioning of the power interface were completed at the Manitoba HVDC Research Centre laboratory. The support of Paul Wilson and Roberta Desserre, the managing directors of Manitoba Hydro International Ltd. and the Manitoba HVDC Research Centre, must be acknowledged.
The author is especially grateful to Randy Wachal, the engineering and research manager at the Manitoba HVDC Research Centre, whose leadership, as well as his insightful pieces of technical advice, made this work possible.

The assistance of Warren Erickson, the technical officer at the Manitoba HVDC Research Centre was instrumental during the construction and field installation phases.

The author is thankful to Erwin Dirks, the University of Manitoba Technologist, for his innovative laboratory test plan to use a tractor’s power take-off shaft in order to emulate a hydrokinetic turbine. This allowed for the successful commissioning of the developed power interface prior to field installation. The generous contribution of Enns Brothers, one of John Deere dealers in Winnipeg, is highly appreciated for providing the tractor used in those commissioning tests.

The cooperation of the staff at Pointe du Bois generating station is recognized for providing logistical support at the installation site in Pointe du Bois, Manitoba.

Once again, the author is grateful to Prof. Ani Gole for his guidance, for leading this project in the right direction, and for his patience during the course of this research.
Dedication

To my parents,

with love.
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<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>AWG</td>
<td>American wire gauge</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DFIG</td>
<td>Doubly-fed induction generator</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed (dispersed) generation</td>
</tr>
<tr>
<td>EMT</td>
<td>Electromagnetic transients</td>
</tr>
<tr>
<td>FACTS</td>
<td>Flexible ac transmission system</td>
</tr>
<tr>
<td>HVDC</td>
<td>High-voltage direct current</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-gate bipolar transistor</td>
</tr>
<tr>
<td>IGCT</td>
<td>Integrated gate-commutated thyristor</td>
</tr>
<tr>
<td>IP</td>
<td>Ingress protection</td>
</tr>
<tr>
<td>LVRT</td>
<td>Low-voltage ride-through</td>
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<tr>
<td>MOSFET</td>
<td>Metal-oxide-semiconductor field effect transistor</td>
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<tr>
<td>PI</td>
<td>Proportional-integral</td>
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<tr>
<td>PLL</td>
<td>Phase-locked loop</td>
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<tr>
<td>PMSG</td>
<td>Permanent-magnet synchronous generator</td>
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<tr>
<td>PWM</td>
<td>Pulse-width modulation</td>
</tr>
<tr>
<td>SPWM</td>
<td>Sinusoidal pulse-width modulation</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Static compensator</td>
</tr>
<tr>
<td>SVC</td>
<td>Static VAR Compensator</td>
</tr>
<tr>
<td>TSR</td>
<td>Tip-speed ratio</td>
</tr>
<tr>
<td>VAR</td>
<td>Volt-Ampere Reactive</td>
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<tr>
<td>VSC</td>
<td>Voltage-sourced converter</td>
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Chapter 1

Introduction

1.1 Background

Rapid growth in energy consumption and environmental concerns over fossil fuel usage have intensified the need for alternative clean energy resources such as solar, wind and hydropower. In the past, techniques for harnessing these sources of energy were considered to be idealistic and experimental; whereas nowadays, many of them are commercially available. Many of these solutions offer cost-effective alternatives, or supplements, to conventional fossil-fuel-based systems. In this way, they seem to provide a solution to problems like emission, high operation costs and increasing gas prices, which are associated with fossil-fuel energy supplies. Moreover, unlike fossil fuels, utilization of a renewable energy source does not affect its availability in the future.

Renewable energy sources are utilized to produce heat, electricity or mechanical energy. The energy of sunshine can be transformed into electricity or heat\(^1\); the energy of falling or flowing water can be converted into electricity\(^2\); the kinetic

\(^{1}\) Solar energy
\(^{2}\) Hydroelectric generation
energy of wind is harnessed to generate electrical power; or the thermal storage capability of the earth could be used for heating and cooling purposes.

Recent years have seen increased interest in distributed generation. Alanne and Saari [1] define distributed energy systems as “efficient, reliable and environmentally friendly alternatives to traditional power generation systems, most of which, are large centralized units that consume fossil fuels to produce heat or electric power.” In contrast, many distributed generation systems seem to benefit from alternative-energy sources.

1.2 Small-Scale Hydropower

Hydropower has been cited as "the most important renewable source of energy" for electricity generation [2]. According to Paish [2], in 1999, large and small hydroelectric power plants supplied over 19% of the electricity demands worldwide, whereas all other renewable sources supplied less than 2% of the global electricity consumption. Paish also refers to World Hydropower Atlas 2000\(^1\) that estimated world's technically feasible hydropower potential to equal the global demand for electrical power.

Small-scale hydro has an immense potential in most regions of the planet, which has not been harnessed. Unlike conventional hydroelectric plants, which require construction of a dam or a barrage, small-scale hydro technologies such as kinetic

\(^1\) Published by the International Journal of Hydropower and Dams
currents, tidal and wave applications, capture the energy in flowing water and convert it into usable energy. Hence, small-scale hydro systems seem to cause minimal environmental impacts, since they require no or very small water storage.

In many remote communities, the transmission grid is not within economic reach. In such areas, electricity is produced by local, often diesel-powered, generator units. In locations where water currents with suitable flow rates are available, small-scale hydro units could be considered as reliable and cost-effective sources of electricity that can serve as the primary electrical supply. They can be supplemented with diesel-generator units, if necessary. Thus, they help reduce emission of the greenhouse gases and the reliance upon fossil fuels.

There is little consensus on the definition of small hydropower. While RETScreen\textsuperscript{®} [3] specifies the rated power output of small-hydro plants in the range of a few kilowatts to over 50MW, Paish [2] suggests that the upper limit varies between 2.5MW and 25MW. Also, RETScreen\textsuperscript{®} introduces a further subdivision of small-scale hydro as mini-hydro in the range of 100kW to 1MW, and defines the range below 100kW as micro-hydro. Paish refers to micro-hydro plants as units smaller than 500kW. Kinetic hydropower is generally classified under the micro-hydro category.

1.2.1 Kinetic Hydropower

Application of kinetic turbines in tidal currents has been reported in the literature, e.g. in [4]-[7]. In this technology, the kinetic energy of tidal currents is transformed
into electric power using submerged turbine-generator sets. The same technique can be used in rivers by installing such underwater turbines (kinetic turbines) in rivers. Kinetic turbines can be relatively inexpensive. They do not require costly infrastructure such as dams or powerhouses.

**Potentials:**

Kinetic turbines are submerged and anchored at suitable locations along rivers where natural land topography restricts the flow, resulting in high local velocities. High-velocity flow also prevents formation of ice, which is a technical concern in areas with extreme winter conditions such as Canada. Hence, the turbine is expected to produce reliable and continuous electrical power throughout the year.

Kinetic hydropower systems (also known as Hydrokinetic) seem to have minimal environmental footprint, since they have no reservoirs and spillways. However, the effect of the underwater turbine on aquatic animals is largely unknown and has to be investigated in a separate study.

Hydrokinetic systems seem to be easily scalable by installing several turbine-generator units in the same current. This allows for construction of kinetic turbine farms.

Harnessing the energy in water currents is similar to converting the wind energy to electricity. However, the density of water is over 800 times larger than that of air. This effects a significant difference between power densities of flowing water and wind. For instance, the power density of a water current flowing at 4m/s, an upper range for rapid water currents, corresponds to that of a hurricane [7]. The power
density of a current flowing at a velocity of 2.3 m/s is equivalent to the power density of a steady wind blowing at 79 km/h [4]. Therefore, a kinetic turbine of a certain power could be built markedly smaller than a wind turbine with similar rated power. In addition to its compact design, the kinetic turbine can generate the same amount of power as its wind counterpart at lower flow velocities. Also, water currents seem to flow at steady and predictable rates compared to wind. Hence, kinetic hydro (also known as hydrokinetic) plants have the potential to produce reliable electric power.

River hydrokinetic power in rivers has not been commercialized. This technology may require the use of underwater turbines in winter-icing conditions and high-velocity rivers with variable flow and high turbulence levels. Impacts of such issues on a kinetic hydro plant have not been fully investigated to date.

**Challenges:**

In contrast to wind generation plants, the design and operation of a river kinetic turbine may appear to be challenging due to the following aspects

- The turbine-generator diameter is restricted by the depth of the installation site, debris, ice floes, etc. (particularly in river applications). This may necessitate the use of high-frequency generators and electronic power interface systems as explained in chapter 4.

- To minimize maintenance requirements, mechanical turbine speed control (e.g. through changing blade pitch angle, etc.) does not seem to be desirable in a
kinetic turbine. Thus, the turbine can only be controlled by adjusting the generator speed using a power electronic converter.

- Conventional closed-loop speed control techniques commonly used in wind turbines may not be suitable in a kinetic hydro plant. Installation of a shaft position (or speed) sensor on the submerged turbine/generator may not be feasible. Also, unlike most wind solutions, the power interface is normally installed on the shore, relatively far from the submerged turbine-generator. Transferring the feedback signal reliably from a shaft position/speed encoder to the power converter over a long distance appears to be challenging. Hence, specialized speed control strategies may have to be devised for kinetic turbines.

- The long cable link between the generator and the power interface may also necessitate additional filtering components to mitigate the negative impact of harmonics on the generator, particularly when high-frequency switching is used in the power interface.

- Depending on its solidity, stopping the turbine rotor may not be feasible in a kinetic hydro application.

- Specialized maximum power tracking schemes may have to be applied to control a kinetic turbine.

The aspects listed above need to be addressed in the design and operation of a kinetic hydro plant.

1.3 Alternative-Energy Power Generation: Technical Concerns

From the environmental perspective, alternative-energy power generation tends to be preferable to conventional technologies. Clean-energy power supplies become
economically appealing due to the fact that unlike conventional power generation systems, clean supplies use energy sources such as wind, flowing water, sunshine, biomass, etc., which are virtually free or inexpensive. However, clean-energy plants may have to be built in locations that are difficult to reach; or their physical structure may make it difficult to perform recurrent maintenance. For example, the nacelle of a wind turbine is installed on a tower that could be as high as 105 meters [8]; kinetic turbines are anchored in relatively swift water currents; and offshore wind farms are not as easily accessible as onshore plants are. Hence, operating costs of an alternative-energy power plant over its lifetime can be kept low only if the apparatus do not require frequent maintenance and overhaul.

Another problem associated with alternative-energy sources is the uncontrollably fluctuating nature of most renewable sources. This is not desirable, particularly when they are utilized for electric power generation. One of the basic requirements of a reliable electrical supply is to provide its load with a constant output; i.e. constant voltage and, where ac loads are concerned, constant frequency. Therefore, the output of an alternative-energy electric supply can only be applied to the load after taking appropriate adjustment measures. In addition, in many applications, it is desirable to maximize the power extracted from a renewable energy source. A combination of electrical and mechanical equipment and strategies might be required to regulate the electrical output of such a power supply to meet the aforementioned requirements. For instance, the electrical output of solar panels is regulated through power-electronic converters, and in some applications, mechanical actuators reposition the panels to track the movement of the sun, in order to maximize the energy capture. In variable-speed wind turbines, the output voltage
and power are regulated by controlling of the generator speed and adjusting the pitch angle of the turbine blades, in addition to slewing the turbine so that it always faces the wind.

1.4 Background of This Work

The focus of this thesis is on the kinetic turbine as one of the feasible options for alternative-energy electricity generation.

In order to examine practical aspects of this technology, an industrial-scale kinetic turbine set-up was designed and constructed [10]. Such a system would provide a platform for research to investigate this renewable energy application from the operation and control perspectives. The size and rated power of this research unit make it usable for supplying actual loads and integrating into the utility network.

To minimize the maintenance requirements of the kinetic turbine, the number of components in the system, especially those located in the water, were reduced. The generator type, the method for transmitting electricity to shore, the location of power conversion and control equipment, etc., all determine the configuration of the power train. Several options for each part of the plant were considered to select the most suitable and flexible configuration for this research platform.

1.5 Major Contributions

1. Development of an approach for harnessing kinetic hydropower

• Several different topologies for a suitable power-electronic interface for harnessing kinetic hydropower were investigated using simulation, and the most
suitable topology was identified. The final power-electronic topology uses back-to-back voltage-sourced converters (VSC) to transform the variable voltage/frequency produced by the generator into a constant ac voltage at the load side.

- Appropriate control strategies that provided adequate steady-state power quality and robust dynamic performance were devised using a simulation-based approach. Power tracking algorithms suitable for kinetic hydro application were also designed.

2. Experimental Validations

- The power train was physically constructed and shown to behave as designed through extensive testing over its full operating range and capacity in a laboratory setting.

- The apparatus was installed in the field (on the Winnipeg river) and shown to work. However, due to poor river flows during the testing period, it could only be tested at a fraction of its full power rating.

3. Investigations into Kinetic Farms

- Using simulation, the possibility of combining multiple kinetic hydro generation systems into a network was investigated. Two feasible options for interconnections (either by using a dc grid or an ac grid) were identified. Control methods for these options were developed.

- Unlike wind, the variations of flow in plants up or downstream from each other is more predictable. The impact of this on the power supply performance and transients was investigated.
1.6 Outline of This Dissertation

The next chapters of this thesis discuss the following aspects.

Components of a typical hydrokinetic plant are explained in chapter 2. Different options for each component are also introduced.

In chapter 3, electronic power conditioning of the power harnessed from alternative energy resources is investigated. Several feasible topologies and configurations are reviewed for interfacing different types of alternative energy sources to standard electric loads. Voltage-sourced converter (VSC) and its control methods are explained.

The design considerations for implementing the power interface developed for this work are described in detail in chapter 4. Several configurations feasible for Hydrokinetic applications are introduced. The rationale behind selecting the components and power interface topology implemented in this work are explained. Simulation results showing the performance of the design are presented. Laboratory tests to confirm those results are also presented.

Some control and operation techniques that can be implemented for a typical hydrokinetic turbine are presented in chapter 5. In hydrokinetic applications, it is desirable to install as few components as possible in the water. Therefore, sensorless control techniques seem to be advantageous. The methods investigated in chapter 5 focus on sensorless turbine control methods, and are studied using electromagnetic-transients-type (emt-type) simulations.
Application of multiple kinetic turbines in a river to form a Kinetic Farm can help increase the power output of a hydrokinetic plant. It can also improve its reliability by introducing redundancy to the system. A few configurations and operating modes that can be considered for Kinetic Farms are presented in chapter 6. Some control schemes are also proposed for coordinating the operation of multiple kinetic turbines to supply a common load. Those aspects are investigated through simulations.

A summary of the contributions in this work is provided in chapter 7. A number of potential topics for future research are also listed in that chapter.
Chapter 2

Hydrokinetic Plants

2.1 Introduction

Hydrokinetic power systems do not require infrastructure such as dams, aqueducts, powerhouses, etc. This attribute distinguishes this technology from other small-scale hydro plants.

A typical hydrokinetic unit is composed of the following basic elements:

- The energy conversion equipment, i.e. a turbine-generator set to transform the mechanical energy of the flow into electrical energy. This component is submerged and is moored to an anchoring structure.

- An electric power delivery system to transfer power to the load.

These components are briefly described in this chapter. Detailed design considerations for a hydrokinetic platform will be presented in chapter 4.

2.2 Hydrokinetic Turbine

In conventional hydroelectric generating plants, the water impounded behind a dam drives hydraulic turbine-generators to produce electric power. In small-scale hydro applications, construction of a dam or barrier may not be feasible or economical.
This hurdle can be avoided by converting the kinetic energy of flowing water directly into electricity using a kinetic turbine-generator.

Kinetic turbines, also referred to as free-flow or in-stream turbines ([9],[11]), are a special class of hydraulic turbines submerged and anchored in rivers or marine currents. They do not need dams or other civil infrastructure, and have small footprint. This makes them attractive for small off-grid applications, particularly in remote communities in the vicinity of rivers that are currently powered by diesel-generators. With adequate flow, the base load can be supplied by a kinetic turbine. The generation can be supplemented by a diesel-generator, if necessary. This can help reduce consumption of fossil fuels and production of greenhouse gases. Where utility network is accessible, excess generation from a kinetic turbine can be provided to the grid.

Kinetic turbines are generally divided into horizontal-axis (axial-flow) and vertical-axis (cross-flow) classes. In horizontal-axis turbines (such as Tyson [4]), water flows parallel to the turbine rotor axis, as indicated in Figure 2-1.

![Figure 2-1: Horizontal-axis turbine with a radius of R.](image)

```latex
\text{Figure 2-1: Horizontal-axis turbine with a radius of } R.\text{ }
```
In a vertical-axis turbine (such as Darrieus, Savonius or Gorlov [9]), the flow passes through the turbine rotor perpendicular to its rotational axis. The schematic diagram of a Darrieus turbine is shown in Figure 2-2.

Figure 2-2: Schematic diagram of a Darrieus turbine.

2.2.1 Power Harnessed by a Kinetic Turbine

Conventional hydraulic turbines are most energy-efficient when used in hydroelectric plants built with dams. A dam raises the water head and increases its potential energy level. This builds up the pressure required to drive the turbine. Turbine efficiency is higher with high water head [9]. In free flow, only the kinetic energy of the stream is utilized, as there is no dam to elevate the head.

Similar to a wind turbine, the power captured by a kinetic turbine from free flow ($P_t$) is obtained from the following equation [7]:

![Schematic diagram of a Darrieus turbine.](image-url)
\[ P_t = 0.5 \cdot C_p \cdot A \cdot \rho_{\text{fluid}} \cdot v_{\text{fluid}}^3 \]  

(2-1)

In (2-1), \( A \) is the turbine cross-sectional area, \( C_p \) is its power coefficient, and \( v_{\text{fluid}} \) is the fluid velocity. Also, \( \rho_{\text{fluid}} \) is the density of the driving fluid. For water it is approximately 1000 kg/m\(^3\).

For a horizontal-axis turbine, the turbine cross-sectional area is circular and therefore, the area \( A \) in (2-1) will be:

\[ A_{h\alpha} = \pi \cdot R^2 \]  

(2-2)

where \( A_{h\alpha} \) is the rotor area and \( R \) is its radius, as shown in Figure 2-1.

The cross-sectional area of a vertical-axis turbine is rectangular. So, its area is:

\[ A_{v\alpha} = D \cdot H \]  

(2-3)

Here, \( A_{v\alpha} \) is the effective area swept by the rotor. \( D \) and \( H \) are the rotor diameter and height, respectively, as denoted in Figure 2-2.

The parameter \( C_p \) is referred to as the power coefficient or the Betz factor. The maximum possible value for \( C_p \) is \( 16/27 \approx 0.5926 \) [7]. The Betz factor is a function of the blade aerofoil profile and its angle of attack (pitch angle), as well as the turbine tip-speed ratio (TSR). TSR is defined as the ratio of the blades’ tip speed to the flow velocity \( v \):

\[ \lambda = \omega \cdot R / v_{\text{fluid}} \]  

(2-4)
In (2-4), $R$ and $\omega$ and are the radius and angular speed of the turbine rotor, respectively. For a fixed-pitch turbine, the power coefficient $C_p$ mainly depends on the tip-speed ratio. Figure 2-3 shows $C_p$ versus TSR ($\lambda$) for a typical horizontal-axis turbine. The maximum power coefficient for this turbine is about 0.47 at $\lambda = 1.87$. The turbine should always operate on the right side of the maximum $C_p$, as denoted in Figure 2-3. Overload can result in under-speed, which drives the turbine operating point to the unstable region on left side of the peak $C_p$. This is an undesirable condition, since cavitation and vibrations may occur, which can potentially damage the turbine blades.

![Figure 2-3: $C_p$-$\lambda$ characteristics for a typical kinetic turbine](image)

The dimensions of a kinetic turbine rotor are fixed and its cross sectional area $A$ is constant. The water density $\rho$ can also be considered constant. Hence, the turbine output power $P_t$ depends on the flow velocity $v_{fluid}$ and the power coefficient $C_p$. For turbines with fixed blade pitch angles, $C_p$ is only a function of the tip-speed ratio $\lambda$. Equation (2-4) can be rearranged as:
\( \omega = \lambda \cdot v_{\text{fluid}} / R \)  \hspace{1cm} (2-5)

Hence, the power \( P_t \) is a function of the flow speed \( v_{\text{fluid}} \) and the turbine speed \( \omega \).

Figure 2-4 depicts the output Power \( P_t \) versus the rotor speed for a horizontal-axis kinetic turbine at different water velocities. The turbine has a \( C_p - \lambda \) curve similar to Figure 2-3, and its radius is 1.25m. The turbine power and speed are given in units of kW and RPM, respectively.

![Figure 2-4: Turbine power-speed characteristics at different water velocities](image)

From (2-1) and the \( C_p \) curve in Figure 2-3, this turbine can produce up to 16kW at a water speed of 2.4m/s. It is observed in Figure 2-4 that the power available at different water velocities depends on the turbine speed. The maximum power can be extracted if the turbine speed is maintained at the TSR corresponding to the
maximum $C_p$. Changing the blade pitch angle is a method to adjust the turbine speed. Although feasible, such a mechanism complicates the mechanical design of the kinetic turbine rotor. Turbine speed can be controlled by adjusting the generator speed using an electronic power interface. This is the basis for the control strategies discussed in Chapter 5.

### 2.3 Generator

Two types of ac generators are reviewed and compared in this section: induction and synchronous. DC generators are not considered in this thesis, since maintenance requirements associated with dc machines make them unsuitable for hydrokinetic plants.

#### 2.3.1 Induction Generator

To operate an induction machine as a generator, it must be connected to a voltage source and should be driven faster than its synchronous speed [28]. Therefore, induction generators seem to be suitable for grid-integrated applications. For islanded operation, external magnetization has to be provided.

Induction generators are mostly utilized in small- and micro-hydro applications where the plant is integrated into the existing ac system [3]. The output power of an induction generator can be controlled by adjusting its rotor slip, either through passive solutions (e.g. by changing the rotor resistance in a wound-rotor induction generator) or using power-electronic drives. The latter can be applied to both squirrel-cage and wound-rotor induction machines.
Supplying islanded loads is an important consideration in this work. Therefore, induction generators were not considered, since they need external excitation to be suitable for this application.

### 2.3.2 Synchronous Generator

Synchronous generator is the suitable option in applications where islanded loads are concerned. A conventional synchronous generator requires dc excitation for its field winding. At a given speed, the output voltage of a conventional synchronous generator is controlled by adjusting its field voltage. Despite the flexibility provided by the field winding, excitation system needs to be installed on the generator. Also, field winding results in a heavy rotor. Those aspects seem to complicate the configuration of the equipment on a hydrokinetic turbine system. This complexity can be avoided by using a permanent-magnet synchronous generator (PMSG). In a PMSG, the no-load terminal voltage is proportional to the rotor speed (i.e. frequency). Unlike conventional synchronous generators, the output voltage of a PMSG cannot be adjusted, since there is no field winding. Generator power regulation is performed using a power-electronic interface.

An off-the-shelf PMSG was selected for the kinetic turbine unit constructed in this work, as discussed in 4.2.2. The specifications of the chosen machine are given in chapter 4 (Table 4-1).
2.4 Power Interface

In contrast to conventional hydro turbines, speed control mechanisms (e.g. variable-pitch blades, adjustable inlet vanes, etc.) complicate the design of a hydrokinetic system. A typical hydrokinetic turbine may not be equipped with mechanical speed control devices. Therefore, the turbine-generator speed will be affected by flow variations, resulting in variable generator output. An electronic power interface is used to condition this output power and supply the load with regulated voltage and frequency. Appropriate strategies can be included in the power interface to control the turbine-generator speed, thus operating the turbine at stable/optimal point.

Power interface systems used in alternative energy applications have different configurations and control methods. Several options are discussed in Chapter 3, with a view to selecting the topologies suitable for a hydrokinetic plant.

The procedure for designing a hydrokinetic power delivery system is explained in detail in Chapter 4.
This section reviews several feasible power conversion systems that are currently used for renewable-energy applications, such as wind and solar. Those options are analyzed, and the configurations that are not suited for kinetic hydro are identified. The candidate topology for the hydrokinetic power delivery train designed in this thesis has been selected based on the analysis in this chapter.

The essential attribute of a premium electric power supply, whether a voltage source or a current source, is the delivery of an output with consistent characteristics. In an electric power system operating under normal conditions, the system voltage must comply with certain criteria defined by standards. For example, 3-phase ac power systems have to provide three balanced [14] sinusoidal voltage waveforms at the standard frequency of 50 Hz or 60 Hz. Standards [15]-[19] specify the permissible ranges of voltage magnitude and frequency variations, harmonic levels, unbalance, etc., that are tolerable by power system components and loads.

Conventional generation systems such as diesel-generators, thermal and hydroelectric power plants employ synchronous generators to produce electric power, where the magnitude and frequency of the output voltage are regulated through appropriate excitation and mechanical input power control, respectively. In
transmission networks, special apparatus such as transformer tap changers, synchronous condensers, static var compensators (SVC), etc. are employed to maintain the voltage level across the grid within acceptable limits.

**Control of Voltage and Power**

The input power applied to a conventional generator is controlled by adjusting the level of energy supplied to its prime mover; for instance, by changing the throttle of a diesel engine, the valve position of a steam turbine, or the gate of a hydraulic turbine. However, most alternative energy resources are of fluctuating and uncontrollable nature and therefore, the electric power produced from such resources has variable characteristics. Hence, alternative-energy electric sources usually have to be linked to electric loads through power interfacing devices. Interface apparatus (or power processors [22]) convert the fluctuating output of the source into a voltage with consistent characteristics suitable for supplying loads or interconnection to the power grid.

Evolution of the power electronics technology has made power-electronic converters more advanced and less expensive. They provide a means to link sources and loads that operate with differing rated voltages and/or frequencies.

The following sections present an introduction to electronic power conversion and discuss a few converter topologies.

### 3.2 Structure of a Power Interface Unit

In this study, only power-electronic interface systems are discussed. The building blocks of a typical power interface are shown in Figure 3-1. Generally, the interface
links two electrical systems with different frequency, voltage and current levels. A controller compares the measured output quantities with the desired reference value(s) and applies proper control signals to the interface, in order to regulate the power exchanged between the two systems.

Diode rectifiers, switching power supplies, 2-quadrant motor speed controllers without regenerative braking, etc., are examples of power interfaces that transfer power in a single direction. Power interface apparatus used for harnessing alternative-energy sources also fall into this category.

In some applications, the roles of load and source may switch. The interface units in such applications must allow for bidirectional flow of power between the linked systems. One of the common uses of this type of power conversion in the industry is the 4-quadrant motor drive with regenerative braking. When braking, the motor operates as a generator and returns energy to the source.
The output of an alternative-energy supply can be either ac or dc. The power interface adapts the supply-side output to conform to the load side requirements. The load system can be an islanded load or the utility grid.

In the islanded operation mode, light load conditions can result in surplus production. This power, if not consumed, may cause undesirable consequences such as over-voltage, or generator over-speeding. In such cases, excess energy may have to be dissipated in a so-called ‘dump load’ (ballast load). It may be possible to utilize this energy for heating/cooling purposes, or to store this energy for use during peak load hours. The storage aspect of kinetic hydro has not been considered in this thesis.

3.3 Classification of Power Interface Types for Harnessing Alternative-Energy Sources

Alternative-energy power interfaces can be classified in four general categories depending on the types of the supply systems and electric loads:

1) dc supply – dc load, 2) dc supply – ac load, 3) ac supply – dc load, and 4) ac supply – ac load. These conversion styles are introduced below.

3.3.1 DC Supply - DC Load

In this class of power conversion, a dc alternative-energy electric source is used for supplying dc loads. Normally, a voltage regulator (e.g. a power-electronic dc-dc converter) supplies the load with a fixed voltage. Solar-powered battery chargers are a common example of this scheme. Also, in large-scale photovoltaic applications, the outputs of multiple solar panels could be linked at a common dc bus after being
regulated by individual dc-dc converters. This regulated dc voltage is then converted to ac to supply standard ac loads.

3.3.2 AC Supply - DC Load

Many alternative energy schemes employ ac generators to produce electric power. Wind and small-scale hydro plants are typical examples of ac power generation. They may be used for direct energization of dc loads; for instance, small-scale hydrogen production using electrolysis [27]. It may also be desirable to transmit the power produced by an alternative source in dc, especially in multi-generator systems. In this case, the dc system is observed by each power interface as a dc load.

The ac-dc converter (rectifier) must be capable of providing regulated dc voltage at its output. Therefore, controlled rectification is essential. There are three options for converting generator variable ac output into regulated dc:

3.3.2.1 Uncontrolled Rectifier and DC-DC Converter

In this scheme, the source ac output is rectified through a full-wave uncontrolled diode rectifier. With a capacitive filter used to remove the voltage ripple, the dc voltage will be the peak of the line-line voltage [23]. The dc output will vary if the ac source voltage (e.g. from a variable-speed generator) fluctuates. Thus, a dc-dc converter is required to regulated dc voltage for the load, as shown in Figure 3-2.

Such a configuration is attractive due to its simplicity. Many dc-dc converter topologies have few switching devices [22]. This could reduce switching losses.
Due to the passive rectification stage, this topology does not seem to be suited for induction generators, since induction machines require external excitation by an ac power supply. This option can be considered as a feasible choice where synchronous generators (conventional or PMSG) are employed.

On the downside, it offers limited flexibility compared to a voltage-sourced converter (explained in 3.3.2.3). For example, speed control strategies commonly used to operate permanent-magnet generators \([19],[43]\) cannot be easily implemented with this configuration. Also, in some topologies (e.g. boost converters) when the conversion ratio between the input and output voltages is high, large filter components are required to prevent discontinuous and inefficient operation \([22]\). Therefore, two or more dc-dc conversion stages may be required to avoid such an issue. This leads to increased component count and is likely to complicate the hardware and control system design.
Hence, although this could be viable in hydrokinetic systems with synchronous generators, the more versatile option explained in 3.3.2.3 (i.e. VSC-based converter) was selected for the set-up implemented designed in this work.

### 3.3.2.2 Conventional Controlled Rectifier

A controlled rectifier can be employed to adjust the dc output, without using an extra stage of dc-dc conversion. The conventional topology for controlled ac-dc conversion is the thyristor-based rectifier. The operating principles of thyristor-based rectifiers are found in textbooks on power electronics (including [22]) and will not be explained in this thesis.

The schematic diagram of a 3-phase full-wave thyristor rectifier is shown in Figure 3-3. The dc voltage of a thyristor rectifier is controlled by appropriate adjustment of its firing angle $\alpha$. The maximum dc voltage is obtained when $\alpha=0^\circ$. At this angle, a thyristor rectifier will be equivalent to a diode bridge.

![Figure 3-3: AC source and dc load configuration: controlled thyristor-based rectifier regulates $V_{dc}$ at the load terminals.](image-url)
Thyristor-based rectifiers offer high power capability at relatively low prices. This topology is the backbone of conventional high-voltage dc (HVDC) transmission. However, they suffer from two major drawbacks:

- The maximum dc voltage of a thyristor rectifier is limited to the peak of the ac line voltage (when a ripple filter is used) [22].
- While at $\alpha=0^\circ$ the thyristor rectifier presents unity power factor, its current phase angle increases as $\alpha$ approaches $90^\circ$, causing the rectifier to exhibit inductive characteristics [22]. Hence, the rectifier demands reactive power from the ac source over the control range of $V_{dc}$. Therefore, the attainable active power level from the ac supply is reduced as the source has a certain rated apparent power.

The above disadvantages made the conventional topology an unsuitable option for the kinetic turbine platform implemented in this study.

### 3.3.2.3 Voltage-Sourced-Converter-Based Controlled Rectifier

Voltage-sourced converters belong to a special class of switch-mode converters [22] used for linking ac and dc systems. If a proper control strategy is used, they permit regulated power exchange between the two sides. VSCs will be discussed more comprehensively in section 3.4.

When used as a controlled rectifier, a VSC can regulate the voltage level at its dc side. The dc side of a VSC is equipped with filter capacitor(s). By absorbing
adequate active power from the ac supply to charge the dc capacitor, the dc voltage can be increased. Although in theory there is no upper boundary for the dc voltage, the maximum dc voltage must be limited to protect the components against over-voltage. Hence, in contrast to thyristor-based rectifiers, the attainable dc voltage in a VSC is not limited to the peak of the ac voltage.

Another exclusive feature of VSCs is their capability to control both active and reactive power levels at the point of interconnection to the ac system.

Despite the flexibilities offered by VCSs, they have a few shortcomings. The main issue (in switch-mode converters in general and VSCs in particular) is the losses caused by the increased number of commutations, especially when the pulse-width modulation (PWM) switching technique [22] is applied. Another disadvantage of the VSC scheme is its high cost-to-rated-power ratio compared to thyristor-based systems. Nevertheless, the increasing use of these power converters in industrial applications has reduced their costs, and with their superior performance, benefits of VSCs overshadow their drawbacks. Therefore, this topology seems to be a suitable choice for alternative-energy projects, including hydrokinetic plants.

3.3.3 Alternative-Energy Schemes Supplying AC Loads

Alternative-energy electricity sources normally have to produce ac voltages in order to supply standard loads. An ac alternative-energy supply may operate in either of the following modes:
• **Isolated operation:** In many applications, particularly in locations where the utility grid is not within economical reach, the power supply must energize islanded loads with regulated voltage and frequency.

• **Grid-connected operation:** If the utility transmission network is accessible, it is desirable to transfer the maximum available power from the alternative-energy source to the grid.

A broader introduction of those modes will be provided in 4.2.4.

### 3.3.3.1 DC Supply - AC Load

In ac systems energized by power supplies such as solar panels or fuel cells, the source dc voltage is transformed into ac through a dc-ac converter (also called an inverter). The inverter regulates the ac voltage in order to meet the load/grid requirements. This type of power conversion is not directly applicable to hydrokinetic, as ac generators are used in such applications. It is explained only to mention one of the possible interfacing configurations. DC-ac converters can form a portion of the power interface in a hydrokinetic system, if an intermediate rectification stage is used to supply dc voltage from the ac generator output.

Two converter topologies can be proposed for the inverter: 1) conventional thyristor-based inverter, and 2) voltage-sourced converter.

#### 3.3.3.1.a Conventional Inverter

Conventional thyristor-based inverters operate on the same principle as a thyristor-based rectifier does. By increasing \( \alpha \) beyond 90° (up to 180°), the polarity of the dc...
voltage is reversed, whereas the direction of the dc current does not change [22]. Thus, the power is transferred from the dc side to the ac system.

Application of thyristor-based inverters is limited to grid-interconnected configurations. Therefore, external voltage support is required at the point of interconnection to the ac network. Also, they can only operate at lagging power factors. Due to those disadvantages especially their incapability of feeding standalone loads, this option is not suitable for a hydrokinetic system and hence, was abandoned in this study.

**3.3.3.1.b VSC-based Inverter**

As stated in 3.3.2.3, VSCs are capable of bidirectional power transmission from ac to dc and vice versa. When operated as an inverter, a VSC appears as an adjustable ac voltage source. VSCs can be used to energize islanded ac loads, or regulate the active and/or reactive power exchange with the grid [48].

**3.3.3.2 AC Supply - AC Load**

Alternative-energy systems that convert mechanical energy into electric power (including wind and small-scale hydropower generation) use two basic types of ac generators, i.e. synchronous and asynchronous.

A synchronous generator can be operated in islanded systems. The terminal voltage of a synchronous generator is regulated by controlling of its field current. Its frequency is adjusted by controlling the speed of its prime-mover.
Asynchronous (induction) generators require external excitation, and are normally operated in conjunction with an energized grid. They follow the ac source frequency. Power regulation is achieved by adjusting their slip [28].

In some applications, the generator voltage and frequency are controlled through conventional mechanisms involving mechanical actuators for speed control and/or simple electrical excitation control. The generator output can be directly applied to ac loads. These methods mostly rely on the adjustability of the input energy. However, the energy obtained from most alternative sources cannot be controlled easily. Electronic power interfaces help expand the generator control range and improve its performance.

AC-to-ac converters typically comprise a rectifier (at the source side) and an inverter (at the load side). In this topology the two converters are linked together at their dc sides (also called dc links or dc buses). Several rectifier and inverter topologies were discussed in the previous sections. The two-stage conversion, i.e. ac-dc-ac, is the basis of the electronic power delivery train implemented for the kinetic turbine platform in this research (see chapter 4). Direct ac-to-ac conversion using matrix converters has also been introduced in the literature [22], but are not commonly used in the industry. Hence, matrix converters were not considered in this work.
3.4 Voltage-Sourced Converter (VSC) and Controlled Power Transfer

In contrast to thyristors, the switching devices in a VSC can be turned on or off by applying appropriate control signals to their gate terminals [22]. This makes VSCs suitable for many tasks that thyristor converters are incapable of performing.

3.4.1 Basic Operation Principles

Switching methods such as square-wave switching, carrier-based pulse-width modulation (PWM) [22],[23], etc. are commonly used to operate voltage-sourced converters. Sinusoidal PWM (SPWM) is explained here as an example. Other methods such as space vector modulation (SVM) [23] can also be used for switching pulse generation, but the same general conclusions apply.

Figure 3-4 shows the structure of a 3-phase 2-level VSC comprising IGBTs [22]. In order to avoid short circuit on the dc bus, only one switch on each leg is turned on at a time. Also, to produce balanced 3-phase voltages, the respective switches on adjacent legs are turned on with 120-degree phase shifts.

**Sinusoidal PWM (SPWM)**

In SPWM, firing pulses are issued based on the comparison between a sinusoidal reference waveform and a triangular carrier [22]. As a result, a pulse train is produced at the ac terminals similar to the one plotted in Figure 3-5. It can be shown that the harmonic contents of the line-line voltage are concentrated in the neighborhood of the switching frequency and its integer multiples [22]. For all
simulation examples used in the design process, the converter was modeled with SPWM.

![Diagram of a 3-phase 2-level VSC with IGBT switches.](image)

**Figure 3-4**: The structure of a 3-phase 2-level VSC with IGBT switches.

**Space Vector modulation (SVM)**

Another common technique for generating switching pulses in a VSC is Space vector modulation [23],[26]. In contrast to SPWM, this method does not require a carrier waveform. In SVM, the reference voltage is normally characterized by a rotating vector. The position and magnitude of this vector are sampled at a given rate. The states and duty cycles for the switches are calculated such that the desired voltage vector is synthesized on average during each sampling interval [23]. The actual implementation used off-the-shelf converters which had SVM built in.

**Effects of Switching Disturbances**

The switching methods mentioned above reconstruct a reference voltage using pulse trains (such as Figure 3-5-b), which contain high-frequency harmonic components.
Harmonics can cause overheating of electrical equipment, malfunctioning of electronic devices, etc. [18]. They may also trigger resonance modes in electric circuits, resulting in harmful over-voltage/over-current conditions in the system.

Figure 3-5: Sinusoidal PWM scheme in a 3-phase VSC (reference frequency: 60 Hz; carrier frequency: 540 Hz). a) Carrier and reference waveforms and switching pulses for Q1. b) Line-line voltage $V_{ab}$.

Another negative impact of switching disturbances arises when power is transmitted via long cables. When exposing a long cable to switching pulse trains, traveling wave effect [14] can yield voltage multiplication across the cable [42], which can damage the cable insulation and the equipment connected at its ends. This is a
known problem in variable-speed motor drive systems where motors are energized by PWM-switched VSCs over long cable links ([43]-[45]).

Hence, the high-frequency switching disturbances must be mitigated. If the frequency of the pulse train is adequately higher (by a factor of 10 or more) than that of the reference voltage waveform these harmonics can be eliminated from the voltage waveform using a passive filter. Such filters commonly comprise series inductors and shunt high-pass branches (as shown in section 4.2.4). Harmonic level constraints are specified in standards, including IEEE Std. 519 [18], and should be considered in the filter design procedure. With a proper filter design, it is valid to assume that the output of a VSC with a sinusoidal reference waveform will be sinusoidal (after filtering). This assumption is used in the following sections.

In most renewable-energy VSC applications, the low-pass filter is arranged in L-C or L-C-L configurations. The design procedure for such filters for a fixed fundamental frequency application is straightforward and is explained in the literature (e.g. in [19]).

3.4.2 Possible Operating Modes

Depending on the systems on its ac and dc sides, a VSC can operate in two modes of operation: Islanded and Grid-connected. Each mode is described below.
3.4.2.1 Islanded VSC Configuration Operation

Voltage-sourced converters can be used as controlled voltage sources to supply islanded ac loads. In such applications, the VSC is supplied from a dc source and produces ac voltage waveforms with controlled magnitude and frequency. This operation mode is used when the ac load system is not supplied by ac grid.

3.4.2.2 Grid-connected VSC Configuration

If VSCs are linked to existing ac grids, it is possible exchange power between the ac and dc systems in both directions. Figure 3-6 depicts the simplified diagram of a voltage-sourced converter connected to an ac system. The VSC block in the figure represents a 3-phase converter. The system on the dc side is shown by a current source to represent the possibility of bidirectional power transfer.

The dc side of a VSC is equipped with a capacitor as a storage element. The capacitor also eliminates/reduces ripple from the dc voltage $V_{dc}$. It is sized for the VSC rated power and a maximum dc ripple at full-load [24]. By controlling the
power balance between the two sides of the converter, the stored energy in the dc-link capacitor can be controlled, thus allowing for adjusting its voltage.

A VSC is usually linked to an ac source through an impedance \( Z_{th} \), which allows the VSC to be connected in parallel with the ac source. This impedance is highly inductive and its resistance can be neglected (i.e. \( Z_{th} = jX_{th} \)). This is a valid assumption, since VSCs are normally connected to the ac grid through filter inductors and/or transformers. The per-phase equivalent circuit of a grid-connected 3-phase voltage-sourced converter is shown in Figure 3-7. The grid is shown as an equivalent voltage source \( V_1 \angle 0 \).

Using phasor analysis for this circuit, the active and reactive power exchanged between the two sources can be obtained as follows:

\[
\begin{align*}
I &= (V_1 \angle 0 - V_2 \angle \delta)/jX_{th} \\
S &= 3 \cdot V_1 \cdot I^* = 3V_1 \cdot (V_1 \angle 0 - V_2 \angle -\delta)/-jX_{th} \\
\Rightarrow \quad \{P = \text{Re}\{S\} = 3 \cdot (V_1 \cdot V_2 \cdot \sin \delta)/X_{th} \\
Q = \text{Im}\{S\} = 3 \cdot (V_1^2 - V_1 \cdot V_2 \cdot \cos \delta)/X_{th}\}
\end{align*}
\]

(3-1)

(3-2)

![Figure 3-7: The equivalent per-phase circuit of a 3-phase VSC linked to an ac source.](image)

The equation set (3-2) implies that the active and reactive power level can be controlled by adjusting the phase angle \( \delta \) and magnitude \( V_2 \) of the VSC voltage, respectively. This is the basis for operating a 3-phase VSC in grid-connected...
configuration. The selection of the magnitude and phase angle can be done using advanced methods, e.g. vector control, that separate and control the active and reactive components of the converter current. Those components are controlled independently to achieve the desired active and reactive power levels [48]. This technique is used in this thesis, and is explained in detail in Appendix A.

3.4.3 Phase Angle and Frequency Measurement in Grid-connected Applications: The Phase-Locked Loop

In grid-connected VSC configurations, the VSC control system adjusts its voltage phase angle with respect to that of the grid voltage in order to regulate the active power. Also, for successful synchronization of the VSC with the grid, the VSC frequency must be equal to the grid frequency. Hence, the phase angle and frequency of the grid voltage need to be detected.

One of the standard methods for measuring the frequency and phase angle of a waveform is the phase-locked loop (PLL) technique. PLL is a device that locks a ‘tracking’ signal onto a reference (or ‘tracked’) waveform by reducing the phase error between them to zero [32]. PLLs can be designed to be unresponsive to disturbances superimposed on the tracked signal, such as harmonics, etc. This attribute makes PLL a suitable solution in power electronics applications.

Several PLL schemes are introduced in the literature (e.g. [19], [32]-[34]). One of the common methods for 3-phase applications is based on selecting the phase voltage $V_a$ as the reference vector [34]. To achieve this, the Park transformation
explained in (A-2) is applied to the 3-phase voltages to map them onto the \(d-q\) plane.

The reference frame angle \(\hat{\theta} = \hat{\omega}t\) used in this transformation is adjusted such that the quadrature (\(q\)) component of the tracked signal is reduced to zero. The block diagram of this strategy is shown in Figure 3-8.

**Figure 3-8**: Block diagram of a PLL, based on aligning the \(d\) axis with voltage \(v_a\)

Assuming the phase voltages \(v_a\), \(v_b\) and \(v_c\) to be defined as:

\[
V_{abc} = V_m \cdot \begin{bmatrix} \cos \theta \\ \cos(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) \end{bmatrix}
\]

(3-3)

the \(abc\) quantities can be transformed into \(dq0\) components using the Park transformation in (A-2):

\[
\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \hat{\theta} & \cos(\hat{\theta} - 2\pi/3) & \cos(\hat{\theta} - 4\pi/3) \\ -\sin \hat{\theta} & -\sin(\hat{\theta} - 2\pi/3) & -\sin(\hat{\theta} - 4\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \times V_m \begin{bmatrix} \cos \theta \\ \cos(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) \end{bmatrix}
\]

(3-4)

In (3-4), \(\hat{\theta}\) denotes the phase angle estimated by the PLL. It will converge to the actual angle \(\theta\) when locking is established.

From (3-4) the \(q\)-axis voltage \(v_q\) is obtained as:
\[ v_q = -V_m \cdot \sin(\hat{\theta} - \theta) \]  

(3-5)

If the estimated angle \( \hat{\theta} \) is close to the actual phase angle \( \theta \), equation (3-5) can be simplified as:

\[ v_q \approx -V_m \cdot (\hat{\theta} - \theta) = -V_m \cdot \Delta \theta \Rightarrow \Delta \theta \propto v_q \rightarrow \text{error signal} \]  

(3-8)

The actual angle can be tracked by reducing the error signal \( v_q \) to zero. This is achieved using the loop filter in Figure 3-8 (i.e. the proportional-integral (PI) block).

The PI controller in this figure outputs the estimated angular frequency for the rotating reference frame. The loop response is improved when the nominal grid angular frequency \( \omega_0 \) is used as a feed-forward input. The estimated angle \( \hat{\theta} \) is obtained by integrating the angular frequency. This angle is subsequently fed back to the Park transformation block, thus closing the loop. The output angle from the above block diagram is a monotonically-increasing/decreasing ramp signal. To avoid potential overflow in actual controllers, the range of \( \hat{\theta} \) variations is limited to a single period of the tracked signal (i.e. from 0 to 2\( \pi \), or from -\( \pi \) to \( \pi \)). This is done by resetting the integrator once \( \hat{\theta} \) reaches one of the angle range limits. Thus, the output of the PLL is a saw-tooth waveform whose frequency equals that of the tracked input and its magnitude is limited between 0 to 2\( \pi \) (or -\( \pi \) to \( \pi \)).

The performance of the explained strategy is demonstrated in Figure 3-9. The PLL maintains locking onto a variable-frequency 3-phase voltage source with a peak phase voltage of 1 kV. In Figure 3-9-a, a step change is applied to the source
frequency from 60 Hz to 100 Hz. It can be observed that the PLL successfully follows the frequency step.

This results in a change in the PLL output angle $\theta_{PLL}$ in order to bring the error ($v_q$) back to zero, as shown in Figure 3-9-b and c, respectively. In Figure 3-9-d, a comparison between the voltage $v_a$ and $\cos(\theta_{PLL})$ indicates that the phase angle and frequency of the source voltage are properly tracked by the PLL. The PI controller
proportional gain and integral time constant are set to 0.3rad/V.s and 0.1ms, respectively.

3.5 Other Considerations in Distributed Generation (DG) Plants

Distributed generation (such as hydrokinetic plants) may not be connected to a bulk transmission system. From the utility grid perspective, they are not treated as conventional power system sources, and are required to follow special regulations such as the recommendations in IEEE Std. 1547 [35],[36]. Some utilities have further guidelines [37] for such resources, which may be stricter than the standard.

Anti-islanding is one of the requirements that need to be considered in a DG plant. Disturbances in the ac grid such as network faults can result in unintentional islanding, where the DG and a portion of the grid become separated from the rest of the utility network. If generation is adequate for the remaining load, the DG installation continues to energize the loads in the island. This is an undesirable operating condition as the DG resource(s) may not be able to maintain the voltage and frequency at their rated values. Also, the lines and transformers in the island may stay energized by an unknown source (i.e. the DG), thus creating a safety hazard for the maintenance crew working on the system. Furthermore, there is a possibility of out-of-phase connection of the grid with the DG when the grid recovers. Standards and utility regulations require that the island be detected and de-energized within two seconds of the formation of the island [36],[37].

Several passive and active strategies have been proposed in the literature for islanding [38]-[40]. A common islanding detection method in power-electronics-
based DG is to monitor the PLL error $\Delta \theta$ [40]. In the event of islanding and loss of grid voltage, the PLL lock is lost and the magnitude of the phase angle error $\Delta \theta$ in (3-8) starts to increase, indicating loss of synchronism. When $|\Delta \theta|$ or the $q$-axis voltage $v_q$ exceeds a minimum threshold, islanding has occurred [40], as shown in Figure 3-10. In this figure, $|v_q|_{\text{min}}$ is the threshold.

![Figure 3-10: Islanding detection based on PLL angle error](image)

In the power interface explained in Chapter 4, anti-islanding detection is performed using a DG protection relay for reliability purposes. It was not implemented in the power interface controls.

A grid-connected DG installation normally supplies local loads. It may also transfer excess power to the grid. In case of intentional or unintentional islanding [35] or re-connection to the grid, it is desirable that the change in the DG operating mode have minimal impact on local loads. Seamless transfer between grid-connected and islanded operation is another feature that may exist in a DG installation [40]. Seamless transfer was not considered in the power interface implemented for this work.
Chapter 4

The Power Delivery Train for the

Proposed Kinetic Hydropower Platform

4.1 Introduction

In a hydrokinetic plant, a turbine-generator set is submerged and moored to an anchoring structure. The generator output is transmitted to the shore over a cable link. It is then applied to the load system through power interfacing apparatus. The generator, the transmission system and the power interface constitute the electric power delivery train of a kinetic hydro platform.

In this research, an industrial-scale kinetic turbine (rated at 60kVA) was designed, constructed and installed on the Winnipeg River in Manitoba in Canada [10]. It is intended for supplying local electrical loads or integration with the utility network.

The turbine speed and hence, the generator output change with flow velocity fluctuations. A power interface was designed and developed to supply the load with regulated voltage and frequency.

The key components of a typical hydrokinetic system were introduced in chapter 2. The design considerations for the developed hydrokinetic platform are discussed in this chapter. The control system is described and the simulation results indicating its
performance are provided. Pre-commissioning tests are also explained and the experimental results are presented.

4.1.1 Challenges

This work revealed a few complications associated with the power interfaces used in hydrokinetic systems. Some of them are briefly explained below.

- Unlike most wind solutions, the submersible turbine called for a remote converter connected to the generator by a long cable. The PWM switching waveforms produced by the generator-side converter would cause over-voltages at the PMSG end due to reflections along the long cable link (120m). Hence, to protect the generator, a low-pass damped filter was added at the converter terminals. This filter is also exposed to a wide range of PMSG fundamental frequency variations (200 Hz to 500 Hz).

To control costs in this research project, selection of components was limited to off-the-shelf elements. This additional limitation resulted in a sub-optimal filter. Simulation and experiment confirmed that the design was adequate for nominal conditions but would not be suitable at the upper extremity of generator speeds.

- Shaft-encoder-based speed measurement commonly used in full-converter wind turbines with PMSG [42] was not possible due to mechanical and electrical integrity issues in installing an encoder on an underwater sealed generator unit. It was also impossible to reliably transfer the signal to the PMSG-side converter located 120 m away on the shore. Hence an alternative approach using a phase-locked loop (PLL) with a wide tracking range was applied in the PMSG-side controls.
The solutions for these issues are discussed in detail in the following sections.

4.2 Basic Components

The constructed hydrokinetic unit comprises a turbine, a generator and an electronic power interface. It is designed to produce up to 60 kW of electric power. The turbine is moored at a location where water flows at relatively high velocities. The mechanical and electrical equipment installed in the water was kept to a minimum to reduce the need for maintenance during operation. In this research setup, the electronic power delivery train and controls are located on the shore. The electrical power produced by the generator is directly transferred to the shore via a cable link.

4.2.1 Design and Structure of the Turbine

A shrouded horizontal-axis turbine [59] with a 2.4-m rotor diameter was designed and built for this project. To provide accessibility over the period of this project, the turbine is mounted on a pontoon system as shown in Figure 4-1. This provides mobility, such that the unit can be moved to different sites. In the final design, the floating platform is not required. The turbine-generator is submerged and anchored below the surface.

The turbine’s designed operating range covers flow velocities varying from 2 to 3 m/s. It can potentially produce up to about 40 kW at a water velocity of 3 m/s.

The analysis in [59] suggests that adding a shroud and diffuser to an axial-flow turbine improves its efficiency. From (2-1), at a water velocity of 5 knots (2.57m/s),
the maximum output power of a turbine with a rotor diameter of 2.4 m and a typical $C_{p_{max}}$ of 0.47 [60] is:

$$P_{t_{max}} = 0.5 \times 0.47 \times \pi \times (2.4 \text{m}/2)^2 \times 1000 \frac{\text{kg}}{\text{m}^3} \times \left(2.57 \frac{\text{m}}{\text{s}}\right)^3 \approx 18 \text{ kW}$$ (4-1)

According to its specifications, the constructed turbine can produce about 23.8 kW at a velocity of 5 knots. This implies that the shroud and diffuser could improve the turbine efficiency by about 32% [59]; i.e. this turbine emulates an unshrouded turbine with a rotor diameter of 2.75 m (15% larger).

**4.2.2 Selection of the Generator**

The kinetic turbine diameter is restricted by the effective cross-sectional area of the stream, particularly in river applications. For axial-flow (horizontal-axis) turbines, the generator and turbine are normally on the same axis. A large generator can interfere with the flow. A heavy machine may also complicate the design of the
supporting structure and make installation more difficult. Hence, compact and lightweight generators are desirable in river kinetic turbines.

In an ac electric machine with sinusoidal excitation, the voltage generated in a stator winding is given by [28]:

\[ E_{rms} = 4.44 \cdot f \cdot N \cdot A_{core} \cdot B_{max} \]  \hspace{1cm} (4-2)

In (4-2), \( E_{rms} \) is the voltage, \( f \) is the frequency of the exciting voltage, \( A_{core} \) is the core cross-sectional area and \( N \) is the number of turns in the winding. At a design flux density of \( B_{max} \) and rated rms voltage \( E_{rms} \), the cross-sectional area \( A_{core} \) can be reduced if a higher design frequency \( f \) is selected, thus reducing the core volume. Hence, size and weight savings can be achieved by using a generator with higher nominal frequency, such as 200 Hz – 500 Hz. This higher frequency can be achieved either by a higher speed or alternatively by a higher number of pole-pairs as is the case in the machine used here\(^1\).

Either induction or synchronous ac generators can be used. Due to the required higher operating frequency and potential islanded load [3], standard induction generators are not suitable for the proposed configuration. For this project, a 24-pole radial-flux permanent-magnet synchronous generator (PMSG) was selected (made by Fisher Electric Technology). Since rotor windings and excitation system do not

---

1 There may be a limitation on the core size reduction when the number of poles is increases. After a certain level, it may not be possible to reduce the core size, since the core has to accommodate the windings that have been distributed into more slots. This was not a limitation in the selected machine.
exist in PMSGs they are simpler than conventional synchronous generators. To regulate the power flow, stator current is controlled via an electronic power interface.

The nameplate data for the PMSG are given in Table 4-1. The PMSG is driven by the turbine through a gear increaser with the generator at the high-speed side. Its nominal frequency is 276 Hz, with a maximum permissible frequency of 600 Hz at a maximum speed of 3000 RPM. The output voltage is proportional to the operating speed and is 304 V (no-load) at the rated speed.

<table>
<thead>
<tr>
<th>Table 4-1: 3-phase PMSG nameplate data (Fisher Electric Technology)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power [kVA]</td>
</tr>
<tr>
<td>Type and number of poles Radial-flux, 24</td>
</tr>
<tr>
<td>EMF constant (line-line-rms) [V/Hz]</td>
</tr>
<tr>
<td>Nominal speed [RPM]</td>
</tr>
<tr>
<td>Nominal frequency [Hz]</td>
</tr>
<tr>
<td>No-load rms line voltage at nominal speed [V]</td>
</tr>
<tr>
<td>Maximum rms current [A]</td>
</tr>
<tr>
<td>Per-phase inductance [μH]</td>
</tr>
</tbody>
</table>

The dimensions and weight of this PMSG is compared in Table 4-2 with those of a standard 60-Hz synchronous generator with similar rated power [62]. It can be observed that the high-frequency PMSG is about 45% lighter than the 60-Hz machine. Its volume is also 47% less than that of the standard generator.

In Figure 4-2, the rms line voltage of the PMSG is plotted versus its speed at no load. Assuming a water flow velocity ranging from 2m/s to 2.56m/s, the no-load PMSG voltage/frequency varies from 261 V/233 Hz to 326 V/291 Hz. Thus, despite
such a wide range of variations at the generator side, the power interface unit must supply the load with fixed voltage and frequency.

![No-load V-f characteristics of the generator in Table 4-1.](image)

Table 4-2: Comparison between the dimensions of the high-frequency PMSG and a standard 60-Hz synchronous generator

<table>
<thead>
<tr>
<th>Generator</th>
<th>PMSG</th>
<th>Stamford UCI224E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>[kVA]</td>
<td>60</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>[RPM]</td>
<td>1380</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>[Hz]</td>
<td>276</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>[V]</td>
<td>304</td>
</tr>
<tr>
<td>Overall length</td>
<td>[mm]</td>
<td>527</td>
</tr>
<tr>
<td>Overall diameter</td>
<td>[mm]</td>
<td>381</td>
</tr>
<tr>
<td>Weight</td>
<td>[kg]</td>
<td>140</td>
</tr>
</tbody>
</table>

4.2.3 Turbine-to-Shore Transmission Schemes

A power interface is required to regulate the variable PMSG output and provide nominal voltage and frequency to the load. The interface consists of a rectifier and an inverter. They are discussed in 4.2.4.
The generator output must be transmitted from the platform to shore via either ac or dc transmission. Several configurations were considered as discussed below. The high-frequency ac transmission explained in 4.2.3.1.b was selected as it was found to be the most suitable configuration.

4.2.3.1 AC Transmission

Two configurations can be proposed for this option: high-frequency ac transmission and power-frequency ac transmission.

4.2.3.1.a Option 1: Power-Frequency Transmission

Both converters of the power interface unit can be installed next to the turbine-generator. The load-side converter produces voltage at power frequency (i.e. 50 Hz or 60 Hz). This power is transmitted to the shore using ac cable.

Since the power electronics and controls are installed in the water, marine-grade switchgear and power-electronic hardware become a necessity. The size and weight of the power interface complicates the design of the mechanical structure. Those issues make this approach unattractive.

4.2.3.1.b Option 2: High-Frequency Transmission

In this scheme, the variable generator output, e.g. a high-frequency PMSG, is directly sent to the shore station over ac cable.

Due to the use of a high-frequency generator, the cable has to carry high-frequency ac currents. The cable must be de-rated in comparison with power-frequency
operation, as the use of a high-frequency increases the cable series reactance and parallel susceptance [54]. According to IEEE Std. 1100 [54], increasing the conductor size above 1/0 AWG (equivalent to 50 mm²) does not offer significant reduction of the wiring impedance at 415 Hz. Parallel cables may be required if the generator current is too high. Also, due to skin effect, the ac resistance rises for higher frequencies and yields higher losses ([54] and [56]-[58]). Here, unlike option 1, the entire electronic power delivery train is located onshore. This is advantageous, since the sophisticated converter systems need not be installed in the water.

4.2.3.2 DC Transmission

It is also possible to transmit rectified generator voltage (dc) to the shore. Two styles can be considered for this method: uncontrolled rectification and controlled rectification.

4.2.3.2.a Option 3: Uncontrolled Rectification

The simplest dc transmission option is to rectify the generator voltage via a diode bridge and transfer the power to shore over a dc cable. A diode rectifier cannot regulate the dc-link voltage. The load-side converter is controlled such that a fixed voltage is produced at its ac terminals. With a diode bridge, sending power to the ac system is possible only if the rectified generator voltage is higher than twice the desired ac peak phase voltage [22]. This constraint may necessitate the use of either a step-up transformer between the generator and the rectifier, or a boost dc-dc converter [22] between the rectifier and the VSC, as depicted in Figure 4-3. The
boost converter can be located either next to the turbine-generator or onshore. The latter seems feasible and attractive. However, as explained in section 4.2.4, VSC-based active rectification was found to be more suitable on the generator side. Hence, this option was ruled out.

4.2.3.2.b Option 4: Active Rectification

An active rectifier is located in the water next to the PMSG. It is a VSC-based ac-dc converter. The conventional thyristor-based scheme has several limitations for this application (as highlighted in 3.3.2.2) and was not considered.

The dc links of the two VSCs in Figure 4-4 are interconnected by a dc cable. The rectifier produces dc voltage, which is transmitted to the shore station over the cable. The inverter transforms the dc voltage to ac at the nominal frequency and voltage levels on the load side.
One of the drawbacks of this method is that the controlled rectifier is located on the boat. This complicates the design, since the control system needs to be split into two sections: one located onboard the boat and the other on land. Therefore, this scheme was not considered. However, it may be a suitable choice for multi-unit applications as discussed in chapter 6.

4.2.4 Power Interface Configuration and Control Strategy

Options 2 (4.2.3.1.b) and 3 (4.2.3.2.a) were initially considered for the power interface. The uncontrolled rectifier topology shown in Figure 4-3-b seemed to be a straightforward and inexpensive configuration. The generator-side converter is mostly composed of passive elements and a single switching valve (in the boost dc-dc converter). The relatively inexpensive diode bridge could be installed in the water next to the generator and dc power could be transmitted to the shore, where the boost converter is located. However, disturbances such as abrupt reductions in load, etc. can result in over-voltages at the dc side of the diode bridge. An additional resistive chopper may have to be connected to the dc side of the diode rectifier in order to protect the dc-dc converter against such over-voltage conditions.
A VSC-based active rectifier has superior performance to a passive rectifier for PMSG control [7]. Reference [7] explains that reactive power adjustment at the PMSG terminal using a VSC-based active rectifier would help operate the machine at its maximum efficiency. The active rectifier topology also offers the possibility to start the generator as a motor. This feature is useful in vertical-axis turbine designs (such as Darreius), which usually are not self-starting [9]. Also, with a slight modification in its control strategy, this configuration can be adapted to be used in kinetic hydro platforms with induction generators.

Hence, due to the advantages explained above, the back-to-back VSC configuration (Option 2 in 4.2.3.1.b) was selected as the final design.

4.2.4.1 Specifications

The power interface supplies a 3-phase ac load at a nominal voltage of 600 V and a frequency of 60 Hz. The 600 V output was selected for connection to a nearby 600 V grid at the site. The permanent-magnet generator’s frequency was assumed to range from 200 Hz to 500 Hz depending on the water speed. The back-to-back VSC system conditions this power to 60 Hz, 600 V.

Selection of the Control Mode for Each VSC

Figure 4-5 presents a schematic diagram of the power interface and its controls. A VSC at the PMSG side converts the PMSG output to a dc voltage. The load-side converter is a voltage-sourced converter (VSC), and inverts the dc voltage to 60-Hz,
600 V three-phase ac voltage. The load-side VSC can operate in grid-connected or islanded modes.

In grid-connected mode, one approach would be to operate the generator-side converter to control active power (e.g. based on maximum power-point tracking (MPPT)). The load-side converter then controls dc voltage and grid-side reactive power [49]. In islanded mode the generator-side converter would have to switch mode to regulate dc voltage. The load-side converter should switch mode to regulate the ac voltage at a fixed frequency [49]. This would require mode switch in both converters. Hence, it was decided to implement an alternative approach, which required a mode change only at the load-side converter. The PMSG-side converter always operates in dc voltage control mode. The load-side converter operates in
power control when connected to the grid. It switches to ac voltage control with fixed frequency when islanded operation is selected.

**Selection of the dc Link Voltage**

In a two level 3-phase VSC, PWM over-modulation can be avoided if the dc voltage is at least twice the peak ac phase voltage [22]. Hence, with the 600 V rms line voltage on the load side, the dc voltage was selected to be 985 V:

\[ V_{dc} = 985V \geq 2 \times \left( 600V \sqrt{\frac{2}{3}} \right) \approx 980V \]  

(4-3)

The load-side converter can be turned on after the rectifier regulates the dc voltage at 985 V.

**Selection of the Converter Ratings**

In order to save cost, the VSC converters are constructed using identical off-the-shelf PM1000 series from American Superconductor®. Both converters are rated at 150 A rms (300 A peak pulse current), 660 V with a switching frequency \( f_{sw} \) of 6 kHz. The two converters are linked at their dc buses through a 1350-\( \mu \)F capacitor, installed internally in the VSCs. On the generator side, the current rating was selected to accommodate the PMSG rated current of 132 A (Table 4-1). On the load side, the voltage rating is suitable for the load (or grid) side voltage of 600 V. With the selected rated current of 150 A, the load-side converter is capable of supplying a 155 kVA load. This rating was chosen to allow for future expansion of the system, such that a second generator and rectifier could be connected to the dc link of this back-to-back converter.
Each converter is discussed below in more detail.

4.2.4.1.a Generator-side Converter

The PMSG-side VSC maintains the dc voltage at 985 V. The maximum operating frequency of the generator was considered to be 500 Hz. Therefore, a switching frequency of 6 kHz was selected. This figure was the maximum permissible switching frequency for the selected converter.

The generator-side VSC is linked to the PMSG via a 120-m-long cable. PWM switching produces steep voltage wave-fronts which trigger travelling wave reflections on long cables [42]. This can lead to insulation failure. Electromagnetic transients (emt) simulations were conducted to determine the susceptibility of the system to such transients.

**Description of the Simulation Case:** This simulation was performed to investigate the severity of voltage spikes observed at the generator terminals. The PMSG was assumed to operate at constant speed, at a typical frequency of 450 Hz. At this frequency, the generator line voltage is 456 V.

The generator was connected to the generator-side VSC via the cable link. The cross-sectional view and dimensions of the cable are shown in Figure 4-7. On its dc link, the VSC was supplied by a constant dc voltage source with a magnitude of 985 V. The VSC was ‘synchronized’ with the PMSG using a PLL, and was operated using sinusoidal PWM. To simulate no-load operation, the VSC modulation index was adjusted to 0.756 to produce a fundamental-frequency voltage equal to that
generated by PMSG. Also, the VSC voltage phase angle was set to zero to maintain zero active power exchange between the machine and the converter.

Figure 4-6-b shows the PMSG no-load line voltage $v_g$. Ringing is observed at each pulse level transition. The PMSG voltage spikes reach 160% of the dc voltage, identifying a potential source for insulation failure. Switching pulses also create current ripple, which can result in generator core overheating, thermal degradation and even destruction of its permanent magnets.

![Graphs showing voltage reflection across a long cable caused by PWM switching.](image)

**Figure 4-6**: Voltage reflection across the long cable caused by PWM switching. a) Line voltage at the VSC terminals. b) Line voltage at the generator terminal, at the receiving end of the cable.

To address both of those problems, a damped low-pass filter (LPF) was added at the VSC end of the cable, as depicted in Figure 4-8-a. The filter comprises a series
inductor \( (L_r) \) and a shunt capacitor \( (C_r) \) in parallel with a damping branch (parallel \( R_{rd} \) and \( L_{rd} \) in series with capacitor \( C_{rd} \)).

![Schematic diagram of the simulated cable cross section](image)

**Figure 4-7: Schematic diagram of the simulated cable cross section**

**Generator-side Filter**

The filter must provide acceptable attenuation for the 6-kHz switching harmonics. At normal generator frequencies (below 500 Hz) it should not distort the voltage. The filter also observes a relatively wide range of PMSG frequency and voltage variations. The filter is shown in Figure 4-8-a, and its elements are selected using the considerations below.

**Selection of the Series Inductance:** The primary purpose of the series inductance \( L_r \) is to alleviate the harmonic content of the ac current. With a switching frequency of \( f_{sw} \) and considering a dc link voltage of \( V_{dc} \), the peak-to-peak ac current ripple \( I_{rpp} \) can be calculated as [50]:

\[
I_{rpp} = \frac{V_{dc}}{8.L_r.f_{sw}}
\]  

(4-4)

Large inductors can lead to sluggish converter response. There are also concerns with their physical dimensions and weight. The series inductance \( L_r \) is typically
selected to reduce the current ripple to a about 15% to 25% of the peak-peak value of rated current [50].

\[ I_{r_{pp}} = \frac{985V}{(8 \times 250\mu\text{H} \times 6\text{kHz})} \approx 82\text{A} \]

This current ripple is 19% of the peak-peak value of rated current.

However, a 250-\(\mu\text{H}\) inductor was not readily available at this converter’s ratings. To save costs, the manufacturer used a 125 \(\mu\text{H}\) inductor instead. At \(V_{dc} = 985\text{ V}\) and
$f_{sw} = 6$ kHz, the current ripple $I_{rpp}$ is 164 A with the new inductance (about 38% of the rated current). This is higher than the maximum recommended level of 25%, but can be handled by the VSC.

**Selection of the Components for the Shunt Branches:** In standard frequency applications (50 Hz or 60 Hz), a common approach is to select a filter cut-off frequency between ten times the ac line frequency and on-half of the switching frequency [49]. This helps avoid the risk of resonance at low- and high-order harmonics. In this design, however, the VSC maximum permissible switching frequency is 6 kHz, while the PMSG frequency was assumed to increase as high as 500 Hz. This is relatively close to $f_{sw}$. Hence, the design rule in [49] could not be applied here. The filter must provide acceptable attenuation for the 6-kHz switching harmonics, while at normal generator frequencies (below 500 Hz) it should not distort the voltage.

Based on the selected inductance of 125 $\mu$H and a -3-dB cut-off frequency of about 3 kHz for the undamped $LC$ filter, the shunt capacitor $C_r$ and the damping branch elements $L_{rd}$, $C_{rd}$ and $R_{rd}$ were designed. Their values are listed in Table 4-3. The selected cut-off frequency is half of the switching frequency, and six times the generator maximum frequency.

| Table 4-3: Generator-side filter components |
|-----------------|--------|------|
| Inductor $L_r$  | [$\mu$H] | 125  |
| Main capacitor $C_r$ | [$\mu$F] | 40   |
| Damping Capacitor $C_{rd}$ | [$\mu$F] | 20   |
| Damping inductance $L_{rd}$ | [$\mu$H] | 56   |
| Damping resistance $R_{rd}$  | [$\Omega$] | 1.6  |
The filter and its voltage gain frequency response \( V_g(j\omega)/V_r(j\omega) \) are shown in Figure 4-8. The voltages \( v_g \) and \( v_r \) are the PMSG- and VSC-side voltages, respectively, as shown in Figure 4-8-a.

The filter was added to the simulation model explained earlier in this section. Results shown in Figure 4-9-b confirm that the designed filter significantly reduces the ringing over-voltages caused by PWM pulses. In that figure, the PMSG was operated at 450 Hz, producing a line voltage of 456 V rms. The VSC modulation index and its voltage phase angle were adjusted to emulate no-load operation.

![Figure 4-9: VSC and PMSG voltages with the low-pass filter. a) VSC voltage. b) Generator voltage.](image)

The damping branch shifts the cut-off frequency to about 2.73 kHz, which was found to be acceptable after extensive emt simulations at different PMSG speed levels. An inevitable disadvantage of the damping circuit in the generator-side filter
is the losses in the damping resistor $R_{rd}$. Simulations revealed that the damping resistors in this design could dissipate up to a total of 2.5 kW when the PMSG operates at maximum frequency.

Simulations were repeated at different PMSG frequency and power levels. The filter was found to perform well over the generator operating range expected in the field.

### 4.2.4.1.b Load-side Converter

The load-side converter is a VSC linking the dc bus to a 3-phase system with 600 V nominal voltage and 60 Hz frequency. It can either supply islanded loads or inject power to the grid. The switching frequency for this converter is 6 kHz.

**Load-side Filter**

Similar to the generator side, the load-side converter is equipped with a low-pass damped LC filter to attenuate switching harmonics ([18],[20], [49],[50]). Designing this filter is more straightforward, since the fundamental frequency (60Hz) is much smaller than the switching frequency of 6kHz. This filter was also implemented using off-the-shelf elements to reduce costs. The single-line diagram of the filter is given in Figure 4-10-a.

Selection of the inductor $L_i$ was a limiting factor here too. As with the generator side, a 125 $\mu$H inductor had to be used. This leads to a current ripple of 38% as explained for the PMSG-side filter. To avoid the risk of resonance at low- and high-order harmonics [49], the cut-off frequency was selected to be 1.5 kHz (i.e. between ten times the line frequency and one-half of the switching frequency [49]). Based on
this cut-off frequency and the selected inductor $L_i$, the component values were selected as listed in Table 4-4.

Table 4-4: Components of the load-side filter

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor $L_i$</td>
<td>[MH]</td>
<td>125</td>
</tr>
<tr>
<td>Main capacitor $C_i$</td>
<td>[μF]</td>
<td>200</td>
</tr>
<tr>
<td>Damping Capacitor $C_{id}$</td>
<td>[μF]</td>
<td>100</td>
</tr>
<tr>
<td>Damping inductance $L_{id}$</td>
<td>[μH]</td>
<td>630</td>
</tr>
<tr>
<td>Damping resistance $R_{id}$</td>
<td>[Ω]</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Figure 4-10: Load-side filter. a) Single-line diagram. b) Bode plot for the voltage gain $V_2/V_i$.

The frequency response of the filter voltage gain $V_2(j\omega)/V_i(j\omega)$ is plotted in Figure 4-10-b. Here, $v_2$ and $v_i$ are load and converter-side voltages, respectively.
4.2.4.2 Control Strategy

The control system block diagram for the power interface is shown in Figure 4-11. The control strategies for each of the two VSCs are explained below.

4.2.4.2.a Control of the Generator-side Converter

The block denoted as “Rectifier Control” outlines the control system for the generator-side converter. The decoupled vector control strategy explained in Appendix A is used in this converter.

PLL as a Substitute for Generator Shaft Position Sensor

In standard PMSG drive applications, the reference angle of the rotating $d$-$q$ frame ($\theta_r$) is normally obtained by monitoring the instantaneous position of the generator rotor using a shaft-mounted position transducer [43]. Installation of a rotor position sensor was not a possibility in the developed platform due to mechanical limitations on the turbine-generator set-up. Also, transmission of the measured signals from a position sensor (in the water) to the PMSG-side converter (on the shore) would add further issues. Hence, it was decided to apply an alternative method.
Figure 4-11: Control system block diagram
The PMSG-side harmonic filter absorbs the rectifier switching disturbances and provides sinusoidal voltages (as in Figure 4-9-b). This allowed for considering the PMSG as a 3-phase ac supply and lock the $d$-$q$ reference frame onto its voltage using a PLL ([32]-[34]). As depicted in Figure 4-11, the voltage at the converter side of the cable is measured and applied to a phase-locked loop. This PLL locks onto the phase ‘a’ voltage in a manner similar to the scheme explained in 3.4.3.

PLL systems used in standard grid-connected VSC applications normally track a voltage with relatively constant frequency (50 Hz or 60 Hz). In contrast, the PMSG frequency varies over a wide range. Therefore, this PLL was designed to maintain lock within a maximum range of 100 Hz to 500 Hz at a maximum change rate of $\pm 100$ Hz/s. Using the PLL output angle $\theta_r$, the instantaneous ac phase voltages and currents are projected onto the rotating $d$-$q$ frame via the Park transformation (denoted by $abc \rightarrow dq$ in Figure 4-11).

**DC Voltage Controller**

The $d$-axis current regulates the real-power component. DC voltage regulation is achieved by appropriately charging or discharging the dc bus capacitor with this power. The dc voltage PI controller in Figure 4-11 regulates the $d$ current reference $i_{dr}^*$ to keep the dc voltage at the desired set-point (i.e. 985 V).

**Generator/Cable Reactive Power Controller**

The generator-side filter reactive power varies with frequency, resulting in a poor generator power factor in certain frequency ranges. Using a second PI controller, the second degree of freedom (i.e. the $q$-axis current reference $i_{qr}^*$) is used to maintain
the total reactive current entering the PMSG and the cable ($i_{iq}$) at zero. This 
effectively improves the generator power factor.

**Vector Control and Switching Pulse Generation**

These reference currents ($i_{dr}^*$ and $i_{qr}^*$) are fed to the decoupled $d$ and $q$ current 
controllers described in Appendix A. The desired voltage references $v_{dr}^*$ and $v_{qr}^*$ are 
produced in this way.

The voltage references are then converted to polar coordinates. Using the magnitude 
$|V_r|^*$ and angle $|\delta|^*$, the space-vector modulation (SVM) block produces switching 
pulses for the IGBTs [23],[26].

In space-vector modulation technique, the desired voltage vector $|V|\angle\delta$ is 
synthesized on average by calculating the duty cycles required for each of the 
switches in the IGBT bridge [23]. In contrast to conventional PWM, no carrier is 
used. Using SVM, the desired voltage can be constructed by fewer switching pulses 
[23], resulting in lower switching losses [26],[26]. The SVM method is employed in 
the converters used in the implemented power interface.

4.2.4.2.b Control of the Load-side Converter

The load-side converter is designed to operate in two modes: grid-connected (Mode 1) and islanded (Mode 2). As indicated in Table 4-5, depending on the mode, 
selectors A, B and C in Figure 4-11 pass the $d$-axis voltage reference $v_d^*$ and the $q$-
axis voltage reference $v_q^*$ to a rectangular-to-polar transformation block (denoted as
\( xy \to \rho \phi \) in Figure 4-11). The outputs are the magnitude and phase angle of the reference voltage (\( |V_t|^* \) and \( \delta_t^* \), respectively). They are then applied to the space-vector modulation (SVM) block along with the corresponding rotating frame angle \( \theta \). The SVM controller generates the switching pulses for the IGBT bridge. Its sampling time and switching frequency are 12 kHz and 6 kHz, respectively.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Switch A ((\theta))</th>
<th>Switch B ((v_d^*))</th>
<th>Switch C ((v_q^*))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>( \theta = \theta_1 )</td>
<td>( v_d^* = v_{d1}^* )</td>
<td>( v_q^* = v_{q1}^* )</td>
</tr>
<tr>
<td>Mode 2</td>
<td>( \theta = \theta_2 )</td>
<td>( v_d^* = v_{d2}^* )</td>
<td>( v_q^* = v_{q2}^* )</td>
</tr>
</tbody>
</table>

**Mode 1 – Grid-connected Operation:** In this mode, the control scheme is based on the decoupled control of \( d \)-axis and \( q \)-axis components of the ac currents \((i_d, i_q)\), as explained in Appendix A. This allows for independent controlling of the \( d \) and \( q \) currents (or equivalently, real and reactive power), such that a change in \( i_d^* \) precipitates a change only in \( i_d \) without causing a change in \( i_q \) and vice versa. The reference angle \( \theta \) required for the Park transformation is obtained by tracking the phase of the grid terminal voltage \((v_{1a})\) using a PLL. The reference currents \( i_d^* \) and \( i_q^* \) are derived from the active and reactive power requirements \( P_{grid}^* \) and \( Q_{grid}^* \) at the point of interconnection, respectively, using relationships in (4-4):

\[
\begin{align*}
i_d^* &= -\frac{2}{3} \times P_{grid}^*/v_{d1} \\
i_q^* &= \frac{2}{3} \times Q_{grid}^*/v_{d1}
\end{align*}
\tag{4-4}
\]

The 2/3 multiplier in (4-4) is due to the form of the Park transformation in (A-2) in Appendix A. The above equations represent an open-loop power control scheme, which regulates the active and reactive power levels at the load-side VSC terminals.
excluding the shunt filter branches. Alternatively, closed-loop regulators can be used. In a closed-loop power controller, the error between the power set-point and the measured power is applied to a PI controller, as depicted in Figure 4-12. The PI controllers’ outputs will be the respective current references.

\[ P_{\text{grid}}^* \rightarrow \text{PI} \rightarrow i_{\text{d}}^* \]

\[ P_{\text{grid}} \rightarrow - \]

Active power control loop

\[ Q_{\text{grid}}^* \rightarrow \text{PI} \rightarrow i_{\text{q}}^* \]

\[ Q_{\text{grid}} \rightarrow - \]

Reactive power control loop

Figure 4-12: Closed-loop active and reactive power controllers

Compared with the open loop option, the reactive power supplied by the shunt filter branch (and its losses) will be eliminated from the process and the net active and reactive power delivered to the grid will be regulated. This method, however, requires additional current sensors to measure the power interface currents at the point of common coupling. The open-loop method was selected in this work, since it was easier to implement.

The active power reference \( P_{\text{grid}}^* \) is normally provided by a turbine control scheme (such as a maximum power point tracking (MPPT) stage [66],[63]). This concept will be discussed in Chapter 6.
As a distributed resource, the power interface should not attempt to actively control the voltage at the point of interconnection to the grid ([35],[36]) as this could interfere with the utility’s voltage regulators, which is not desirable. At certain network operating conditions, however, the generation delivered to the network may affect the voltage profile. Therefore, the grid operator may specify a reference for the reactive power supplied or absorbed by the converter unit (i.e. $Q^*_{\text{grid}}$) to ensure that the acceptable voltage limits of ±5% are not violated [36]. This mechanism is not available at the installation site. Hence, it was decided to set the reactive power set-point $Q^*_{\text{grid}}$ such that the converter would operate close to unity power factor by absorbing the capacitive reactive power supplied by the filter at 1p.u. grid voltage frequency. The shunt filter branches would supply about 41kVAr capacitive reactive power at a voltage of 600V. Hence, $Q^*_{\text{grid}}$ was set to +41kVAr, representing reactive power absorption.

**Mode 2 – Islanded Operation:** In the islanded mode, the converter is disconnected from the grid and supplies the load bus with fixed voltage. The reference angle $\theta_2$ is generated directly from the desired frequency $f_0$ (60 Hz in this application) using a voltage controlled oscillator (VCO). The VCO is similar to the final stage of the PLL scheme explained in 3.4.3. Since there is no ac voltage in the system to lock onto, a full PLL is not necessary, as shown in Figure 4-13. The VCO generates a sawtooth waveform that varies from 0 to $2\pi$ (or $-\pi$ to $\pi$) at a frequency equal to the set-point $f_0$, similar to Figure 3-9-b.
In this mode, the converter supplies a passive load. Therefore, the real power absorbed from the converter \( P_{\text{load}} \) is determined entirely by the ac voltage magnitude \(|V|\) and the load impedance \( Z \angle \phi \):

\[
P_{\text{load}} = \text{Re}\{ |V|^2 / Z \angle \phi \} \tag{4-5}
\]

Since the phase of the generated waveform in arbitrary, only one of the \( d \)- or \( q \)-axis voltages needs to be controlled and the other reference can be set to zero. Here the \( d \)-axis voltage reference \( (v_{d2}^*) \) is produced by a PI controller that acts on the error between a set-point and the measured load bus voltage. This is shown in the sub-block at the bottom right in Figure 4-11. The \( q \)-axis voltage order \( (v_{q2}^*) \) is set to zero. Selector switches A, B and C are appropriately set (as shown in Table 4-5) to pass these signals onwards to the SVM module.

### 4.2.4.3 Resistive Chopper Circuit

At certain operating conditions (such as low load and high flow) or disturbances (e.g. when a large portion of the islanded load is disconnected), the generator-side converter may not be able to maintain the dc link voltage. This may cause a temporary and uncontrollable rise in the dc voltage. To protect the equipment, it may be necessary to add a resistive load (also known as ‘dump load’) in the form of a dc chopper, as shown in Figure 4-14. In case of an uncontrolled dc over-voltage,
the chopper switches the resistance on and forms a parallel RC circuit with the dc link capacitor. This will help discharge the excess energy in the dc capacitor into the resistor.

![DC Chopper Diagram](image)

**Figure 4-14: DC chopper for dc over-voltage protection**

In the implemented research system, however, simulations did not indicate a need for a dc chopper for the studied load disturbances. Also, space and cost constraints would not allow this item to be included in the power converter. Therefore, this branch was not considered in the design.

### 4.3 Simulation of the Two Operating Modes

Electromagnetic-transients-type (emt-type) simulation was used extensively to validate the control strategies explained in the previous section.

The system in Figure 4-11 was implemented in the simulation cases. This system closely represents the interconnection to the utility grid at the installation site. Figure 4-15 to Figure 4-18 present the simulation results for grid-connected operation. Results of the simulation tests for islanded mode are shown in Figure 4-21 and Figure 4-22. The turbine is not modeled in these simulation results. Turbine modeling will be explained in 5.2. In the simulations, the PMSG was driven by a
speed-controlled prime mover. The same configuration was later set up in the laboratory for the pre-commissioning tests, as explained in the following section.

The start-up and no-load operation of the generator-side and load-side converters are plotted in Figure 4-15 and Figure 4-16, respectively.

### 4.3.1 Converter Start-up – Generator side

In these simulations, the PMSG was nominally driven at about 1400RPM, corresponding to a frequency of 280 Hz. This is close to the PMSG’s nominal frequency. The generator no-load voltage is 325 V (rms). Prior to starting the rectifier, the shunt filter branch supplies about 20 A (rms), i.e., about 10.35 kVAR at 325 V and 280 Hz. As observed in Figure 4-15-b, in steady-state operation, the rectifier absorbs the reactive current and regulates the dc voltage at 985V.

![Figure 4-15: Generator-side converter start-up and no-load operation.](image)

a) PMSG and dc-bus voltages. b) PMSG current.
4.3.2 Converter Start-up – Load side

The load side converter is turned on after the dc voltage reaches the set-point, as shown in Figure 4-16. Prior to starting, the load-side filter supplies about 41 kVAr capacitive reactive power at 600 V and 60 Hz.

![Figure 4-16: Load-side converter start-up in grid-connected mode with $P_{grid}^* = 0$.]

- (a) Grid and dc-bus voltages.
- (b) Grid current at the 600 V side.

The reactive power reference $Q_{grid}^*$ is adjusted to 41 kVAr, such that the converter would absorb the reactive power upon start-up and operate at unity power factor. This is observed in Figure 4-16-b, as the grid current magnitude is dropped. The active power reference $P_{grid}^*$ is at zero in this simulation.

4.3.3 Robustness of the Scheme - Against PMSG Speed Fluctuations

In the next set of simulations, the generator speed was ramped up/down, in order to verify the robustness of the generator-side converter against the PMSG frequency fluctuations caused by flow variations. As an example, the PMSG speed was
changed from 1400 RPM to 1800 RPM at a rate of 200 RPM/s. This is similar to a situation when the water velocity increases, causing a rise in the turbine-generator speed. The tested speed range corresponds to frequencies from 280 Hz to 360 Hz. Results are shown in Figure 4-17 and Figure 4-18.

Figure 4-17: Impact of increasing the PMSG speed from 280 Hz to 360 Hz. a and b) PMSG active and reactive power. c) PMSG frequency. d and e) grid active and reactive power.
In Figure 4-17, the active power reference $P_{grid}^*$ is kept at 40 kW. The active power levels absorbed from the PMSG and delivered to the grid are not affected, as shown in Figure 4-17-a and d, respectively.

Figure 4-18: PMSG and rectifier responses to an increase in the generator speed.

a) PMSG frequency. b) PMSG and dc voltages. c) PMSG current.

The PMSG current reduces as the PMSG speed and voltage increase. This is shown in Figure 4-18-c. The rectifier successfully maintains the dc voltage at 985 V, as observed in Figure 4-18-b.
4.3.4 Grid-connected Mode: Robustness Against Power Set-point Changes

Figure 4-19 depicts the converter responses to a step change in the active power set-point $P^*_{\text{grid}}$ from 20 kW to 40 kW. For the scenario shown in Figure 4-19, the power levels at each side of the interface are presented in Figure 4-20.

Figure 4-19: Step change in the active power reference $P^*_{\text{grid}}$ from 20 kW to 40 kW. a) PMSG and dc-bus voltages. b) PMSG current. c) Grid and dc voltages. d) Grid current.
The load-side converter delivers the demanded active power at unity power factor by absorbing power from the dc bus. This attempts to discharge the dc capacitor and consequently, the dc-bus voltage drops. The rectifier readjusts the dc voltage by absorbing active power from the PMSG (Figure 4-20-a) while maintaining its reactive power level close to zero (Figure 4-20-b).

Figure 4-20: Active and reactive power levels at each side of the power interface. a and b) PMSG active and reactive powers. c and d) grid active and reactive powers.
4.3.5 Islanded Operation - Robustness Against Load Disturbances

As discussed earlier, the converter has the capability of being the sole supplier of an islanded load, which has no grid connection. The performance in the islanded mode was investigated through simulations. The waveforms in Figure 4-21 correspond to the converter start-up in islanded mode under no load conditions with the PMSG running at 285 Hz frequency. Responses of the two converters to a load change are presented in Figure 4-22.

Figure 4-21: Converter start-up in islanded mode, under no-load conditions.
(a) PMSG and dc voltages. b) PMSG current. c) DC and load 3-phase ac voltages.
Figure 4-22: Applying a 20 kVA load to the power interface. a) PMSG and dc voltages. b) PMSG current. c) DC and load voltages. d) Load currents. e) Load rms voltage.
In Figure 4-21, first the generator-side converter starts at $t = 0.1$ s. It regulates the dc link voltage to the set point of 985 V and adjusts the PMSG reactive power at zero, as indicated in Figure 4-21-a and b, respectively. In Figure 4-21-c, the load-side converter starts at $t = 0.2$ s and regulates the ac voltage at 600 V. To avoid a high inrush current for charging the filter capacitors, the inverter output voltage is increased at a limited rate upon start-up. The dc voltage dip and generator current rise observed in the plots at $t = 0.2$ s are due to the filter capacitor charging transient.

In Figure 4-22, a 20-kVA load with a 0.85 power factor (lagging) is applied to the load-side converter. The rectifier successfully maintains the dc voltage. Also, the load-side converter regulates the load voltage at 600 V, as depicted in Figure 4-22-e.

### 4.4 Laboratory Tests

Pre-commissioning tests were performed at the Manitoba HVDC Research Centre in Winnipeg, Canada. The developed converter is shown in Figure 4-23.

The constructed power interface was operated in conditions similar to those in the field. The PMSG was driven by a variable-speed prime mover. The power take-off (PTO) shaft of an 83-hp tractor (≈ 62 kW) was used for this purpose, as indicated in Figure 4-24-a.

The load-side converter was connected to a 600 V feeder rated at 40 A. It was operated in the grid-connected mode. This enabled near full-power testing the PMSG and the power interface up to 50 kW (the generator is rated at 60 kVA at
unity power factor). As per the design requirements explained in 4.2.4.1.b, the reactive power set-point was set to 41 kVAr to absorb the load-side filter’s capacitive reactive power. Similarly, the PMSG-side reactive power control loop (explained in 4.2.4.1.a) absorbed the capacitive reactive power supplied by the generator-side filter at different PMSG frequency/voltage levels. The active power set-point $P_{grid}^*$ (Figure 4-11) was manually changed to vary the power transferred from the generator to the grid.

![The developed power interface cabinet](image)

Figure 4-23: The developed power interface cabinet

Some steady-state and dynamic test results are presented in Figure 4-25 to Figure 4-29. The experiments explained here confirm the simulation results presented in the previous section.
4.4.1 No-load operation

When both converters were turned off, the capacitive filter branches on the PMSG side would supply about 20 A at a generator speed of 1400 RPM (280 Hz frequency). This is in the speed range expected at the installation site. The grid-side filter capacitors supply 27 A of reactive current. The no-load operation is shown in Figure 4-25. Once the converters are started, they absorb the reactive currents.

Negligible currents flow to the PMSG and grid at no load, as can be observed in Figure 4-25-a and Figure 4-25-b, respectively.

In those plots, the disturbance seen on the generator current is due to noise picked by the current transformer used for waveform recording.
4.4.2 Full-load operation

The voltage and current waveforms shown in Figure 4-26 correspond to $P_{\text{grid}}^* = 49$ kW (close to full load). The PMSG voltage and currents are given in Figure 4-26-a. The PMSG was running at 270 Hz and 294 V. It provided 98 A in steady state. The grid voltage and current are also shown in Figure 4-26-b.

Figure 4-26: Load test at 49 kW power order. a) PMSG voltage and current, and the dc bus voltage. b) Grid voltage and current.
4.4.3 Impact of Speed Variations

The PMSG speed was changed under all load conditions using the variable-speed prime mover. The interface successfully handled the speed fluctuations. The delivery of power to the grid side was not interrupted.

![Figure 4-27: Voltages and currents at two different generator frequencies, with $P_{grid}^* = 40$ kW.](image)

(a) PMSG and grid voltages and currents at $f_g = 305$ Hz.
(b) PMSG and grid voltages and currents at $f_g = 236$ Hz.

The system voltages and current waveforms presented in Figure 4-27-a and Figure 4-27-b correspond to a power order of 40 kW with the generator driven at 1525 RPM (305 Hz) and 1180 RPM (236 Hz), respectively. The speed was changed while the converters were on line and delivering 40 kW to the grid. The PMSG-side
converter successfully supplied the load-side VSC with a regulated dc voltage, while maintaining the PMSG power factor at unity.

4.4.4 Dynamic Response to Load Disturbances

Islanded operation was studied in detail through emt simulation, as explained in 4.3.5. This mode could not be tested, since a load bank of adequate ratings was not available. During the lab tests, robustness of the controls was investigated by applying step changes to the set-point $P^*_{grid}$ while the interface was on line and running. This effectively represented load fluctuations in islanded mode. The dynamic response of the generator-side converter was verified by monitoring the dc bus voltage. Some results are shown in Figure 4-28 and Figure 4-29. The voltages and currents in Figure 4-28 correspond to a step change in $P^*_{grid}$ from 20 kW to 40 kW. The PMSG voltage and current in Figure 4-28-a do not have the same resolution as the grid-side waveforms in Figure 4-28-b, since the PMSG was operating at 272 Hz. The increase in power demand results in discharging the dc capacitor and causes a dip in the dc voltage. The dc voltage regulator in the PMSG-side converter increases the active current absorbed from the generator to charge the capacitor and compensate for the voltage drop. After a few damped oscillations, the dc voltage is stabilized at the set-point. The waveforms in Figure 4-29 present the PMSG and grid voltage and current due to a drop in $P^*_{grid}$ set-point from 23 kW to zero.
Here, the steady power demand from the ac side is suddenly cut off, whereas the PMSG-side converter still tries to transfer power to the dc link. This charges the capacitor up, leading to a temporary rise in the dc voltage. The dc controller then reacts and reduces the power absorbed from the generator to readjust the dc voltage at the set-point under the new operating conditions.

4.5 Field Installation

In the autumn of 2011, the developed kinetic turbine and power interface were installed in the field at Pointe du Bois in Manitoba in Canada. The turbine is shown
in Figure 4-30. Figure 4-30-a shows the turbine before being lowered into the water.

In Figure 4-30-b the turbine is submerged and is in operation. The power interface was integrated into the grid at 600 V, 60 Hz.

Severe lack of precipitation in 2011 resulted in low water flow (<1 m/s) at the site. This was much lower than the turbine’s design minimum water speed of 2 m/s. The turbine could only be loaded up to less than 10% of its rating. To resume long-term operational tests, the turbine will have to be installed when water flows recover to normal operation levels which are typically in the range between 2.1 and 2.5 m/s.

![Figure 4-30](image)

(a) Turbine raised above water. b) Immersed turbine, in operation.

### 4.6 Concluding Remarks

The performance of the controllers for the implemented hydrokinetic power interface was demonstrated in this chapter through a simulation-based design approach. Experimental results were also obtained on the designed apparatus. The power interface was found to be capable of delivering power at unity power factor to the grid, while maintaining the dc bus voltage and operating the PMSG at close to
zero reactive power. The performance of the system was also acceptable in the
islanded mode, where the load-side converter adequately controls voltage and
frequency. Hence, the designed power train is suitable for use in the field.
Chapter 5

Turbine Control and Maximum Power-Point Tracking

(MPPT)

5.1 Introduction

In many renewable-energy generation plants such as solar, wind and kinetic hydropower applications, the amount of energy converted to electricity is not controllable on demand. Therefore, it is desirable to extract the maximum available power from the energy source at each instant, e.g. using a maximum power-point tracking (MPPT) control strategy. This type of control is normally advantageous in grid-connected configurations, where surplus power can be sent to the utility grid when little power is absorbed by the local consumers. However, this technique may also be applied to islanded load systems by storing the excess energy (e.g. battery storage, etc.) or converting the produced electricity into other usable forms of energy (e.g. to provide hot water, etc.).

The turbine control techniques explained in this chapter are intended for implementation on the power interface discussed in 4.2.4. They were validated through emt-type simulations, as low water flow at the installation site did not provide the opportunity to test those schemes in the field. The discussion starts with describing the method used to represent the turbine in the simulations. It is then followed by introducing a few tracking strategies. Acceptable performances of those
schemes are confirmed by the simulation results presented for each of the explained methods.

5.2 Modelling the Hydrokinetic Turbine

Detailed hydraulic and mechanical aspects of turbine modelling are out of the scope of this thesis. The method explained in this section uses the PMSG specifications discussed in section 4.2. It can be applied to any type of hydrokinetic turbine.

The power output from a kinetic turbine at a given water velocity $V_w$ is obtained from (2-1). It was concluded in 4.2.1 that a shroud would allow the turbine to exhibit the performance of a unit with no shroud but at a larger effective diameter. Hence, it is acceptable to assume that the turbine under study has a rotor diameter of 2.75m with no shroud. The $C_p$-$\lambda$ characteristics were not available for the turbine and remain proprietary. To allow for simulation tests, a typical profile similar to the one introduced in [60] was used. At a water velocity of 4.8 kn (2.47 m/s) and under full load, it was assumed that the rotor would rotate at 31RPM. This represents a tip-speed ratio (TSR) equal to:

$$\lambda_{full \, load} = \frac{R \cdot \omega}{V_w} = \frac{1.375 \text{m} \times 2\pi \times 31 \text{RPM}}{\left(60 \text{s} \times 2.471 \text{m/s}\right)} \approx 1.807 \quad (5-1)$$

The $C_p$-$\lambda$ curve assumed for this horizontal-axis turbine is shown in Figure 5-1. At $V_w = 2.471 \text{m/s (4.8kn)}$, the turbine no-load speed is about 59RPM. This corresponds to $\lambda \approx 3.45$. The maximum power coefficient and its respective TSR are denoted as $C_{p_{max}}$ and $\lambda_{opt}$, respectively.
In emt-type simulation programs, the interface between electric machine models and mechanical systems (i.e. loads or prime movers) is through the rotor speed $\omega_r$ and the mechanical torque $T_m$. When operating as a generator, a machine receives mechanical torque from the prime mover and outputs its rotor speed. The interface variables between the kinetic turbine model and a permanent-magnet synchronous machine are indicated in Figure 5-2-a. From equation (2-1), the turbine output power $P_t$ depends on the water velocity $V_w$ and the power coefficient $C_p$. Assuming a fixed pitch angle for the turbine blades, the latter is related to the TSR ($\lambda$). Hence, the turbine output torque $T_t$ can be obtained from the following equation:

$$T_t = P_t / \omega_t = \frac{0.5 \cdot C_p(\lambda) \cdot A_t \cdot \rho_w \cdot V_w^3}{\omega_t}$$

(5-2)

where $A_t$ is the turbine cross-sectional area, $\omega_t$ is the turbine speed and $\rho_w$ is the density of water. The turbine and the generator are normally linked via a step-up gearbox with the generator at the high-speed side:

$$\omega_t = \omega_g / n \ ; \ n > 1$$

(5-3)
In equation (5-3), \( n \) is the gearbox ratio. Assuming a gear-increaser efficiency of \( \eta_{gb} \), the output power at the high-speed side of the gearbox \( (P_{mg}) \) will be:

\[
P_{mg} = \eta_{gb} \cdot P_t
\]  

(5-4)

Figure 5-2: Kinetic turbine model. a) Interface with PMSG. b) Turbine model block diagram.

TSR \( (\lambda) \) is in turn a function of \( V_w \) and the turbine tip speed \( R \cdot \omega_t = R \cdot \omega_g / n \).

Thus, the power coefficient \( C_p \) is a function of variables \( V_w \) and \( \omega_g \). From (5-2) and (5-4), the mechanical torque at the generator side \( (T_{mg}) \) can be written as:

\[
\begin{align*}
T_{mg} &= \left[ K \cdot \eta_{gb} \cdot C_p \left(V_w, \omega_g\right) \cdot V_w^3 \right] / \omega_g \\
K &= 0.5 \cdot A_t \cdot \rho_w
\end{align*}
\]  

(5-5)

Here, \( K \) is a constant. Based on (5-5), the turbine model can be developed as shown in Figure 5-2-b. \( C_p \) can be represented by a look-up table based on the turbine characteristics obtained from tests and design information [60].
5.3 Kinetic Turbine Control Schemes

It is normally desirable to extract the maximum energy available from alternative energy systems such as solar, wind or kinetic hydro power, as they are supplied by energies that are virtually free. Those resources are often of variable and unpredictable nature. The power interface in such applications should be controlled to automatically account for input energy fluctuations. It should operate the energy conversion device (e.g. turbine) at its optimal point while supplying the load system with maximum available power. This strategy is often referred to as maximum power-point tracking (MPPT).

Due to similarities between wind and hydrokinetic turbines, the control methods used in wind generation systems are expected to be valid in kinetic hydro. There are, however, differences that need to be considered:

- Water turbine blades are vulnerable to cavitation. This phenomenon can occur, for instance, due to overloading and operation in the unstable region shown in Figure 2-3.

- Water turbines may have high solidity (e.g. horizontal-axis). Unstable operation may lead to stalling, which may be detrimental to the turbine and/or its associated mechanisms.

- Obtaining feedback from water velocity does not seem to be as easy as measuring wind speed on a wind turbine. A water speed measurement sensor is exposed to debris and other floating objects and thus, is prone to damage. Transmitting the measurement signals from the sensor (in the water) to the control system (located on the shore) also may not be straightforward. For the
same reasons, turbine-generator speed sensors are not desirable either. Also, maintenance and repair requirements can be reduced by installing as few components as possible in the water. Hence, sensorless methods seem to be superior in controlling hydrokinetic turbines.

Therefore, conventional tracking methods in wind applications may need to be modified to meet the aforementioned considerations. Among the turbine control methods presented in [63] to [65], two techniques seem to be suitable for kinetic hydro applications: the maximum power-point tracking (MPPT) and the optimal power control based on the turbine model characteristics. Those schemes do not require feedback from water speed. However, they need turbine speed measurement.

Since a PMSG is used in this work, the generator frequency closely represents the turbine speed. Hence, no turbine speed transducer is required. This feature is utilized to customize the methods mentioned above for this application. The modified methods will be demonstrated through emt-type simulation results.

5.3.1 MPPT Based on Perturb-and-Observe (P&O)

One of the tracking algorithms commonly used in solar and wind applications is the perturb-and-observe (P&O) strategy [66]. In this method, power coefficient characteristics are not required. This is advantageous if turbine characteristics such as the $C_p-\lambda$ curve or the maximum power coefficient $C_{p_{max}}$ and its respective tip-speed ratio $\lambda_{opt}$ are not readily available. The active power set-point is automatically adjusted such that the turbine always operates in the stable region and delivers the maximum available power.
The power-vs.-speed characteristics of the turbine described in 5.2 are plotted in Figure 5-3 at three different water velocities ($V_w$): 2.06m/s, 2.27m/s and 2.48m/s (corresponding to 4kn, 4.41kn and 4.8kn, respectively).

Regardless of the water speed and the $C_p$-profile, the stable operating region is at the right side of the peak power, where the slope of the curve ($\Delta P / \Delta N$) is negative. In this region, an increase in the turbine load causes the turbine speed to reduce. If the turbine operating point is on the right side of the peak power in Figure 5-3, the turbine will be capable of driving the mechanical load. When the operating point reaches its peak power, increasing the mechanical load will overload the
turbine, thus driving it to the left side of the power-vs-speed curve. This can lead to cavitation and can potentially stall the turbine.

The MPPT algorithm attempts to maintain the operating point on the right side of the power curve. The slope $\Delta P_t / \Delta N_t$ is calculated at suitable time intervals. The power set-point is changed until the slope is close to zero and slightly on the negative side [63]. This helps prevent the MPPT controller from constantly searching for the peak point, which can cause undesirable set-point fluctuation, or may even lead to driving the turbine into the unstable region. Calculation of $\Delta P_t / \Delta N_t$ is described below for a PMSG-based system.

5.3.1.1 Calculation of the Slope $\Delta P_t / \Delta N_t$

The PMSG and the turbine are linked via a gear increaser with a ratio of $n$. The PMSG frequency $f_g$ is directly proportional to the turbine speed $N_t$, since:

$$N_t = \left(120f_g/p\right) \cdot 1/n$$  \hspace{1cm} (5-6)

where $p$ is the number of poles of the PMSG. For the turbine set-up in this study, the pole number $p$ and gearbox ratio $n$ are 24 and 42, respectively.

Figure 5-4-b depicts the slope variations of the turbine power $P_t$ versus $f_g$. It can be observed that the slope $\Delta P_t / \Delta f_g$ can identify the turbine operating region.

The generator power $P_g$ can represent $P_t$, as:

$$P_t = P_g / \left(\eta_d \cdot \eta_g\right)$$  \hspace{1cm} (5-7)
where $\eta_d$ and $\eta_g$ are the efficiencies of the mechanical drive-train and the generator/cable, respectively. Hence, the slope $\Delta P_g/\Delta f_g$ can be used as a substitute for $\Delta P_t/\Delta f_g$ to determine the turbine operating region.

The PMSG power $P_g$ can be calculated from the voltage and current measured at the rectifier terminals. The frequency $f_g$ can be obtained using a PLL, as explained in 4.2.4.1.a. Therefore, the ratio $\Delta P_g/\Delta f_g$ can be formed from the voltages and currents measured at the rectifier. No speed sensors are required.

![Figure 5-4: a) Turbine power curve at $V_w = 2.27$ m/s. b) Slope variations vs. PMSG frequency.](image-url)
5.3.1.2 Tracking Algorithm

To track the maximum power point, the control system starts with sampling the generator power $P_g$ and frequency $f_g$ at an appropriate rate. In order to attenuate the effect of rapid transient fluctuations caused by turbulence, etc., a smoothing filter (such as moving average) is applied to the measured $P_g$ and $f_g$ signals. The averaged values $<P_g>$ and $<f_g>$ are then sent to the tracker scheme shown in Figure 5-5. The output of the MPPT controller in Figure 5-5-a is the power set-point $P_{grid}^*$, which is applied to the inverter-side converter in this platform, when operating in grid-connected mode.

The MPPT set-point rate function in Figure 5-5-c provides the desired rate for changing $P_{grid}^*$. The power-speed ($P_r$-vs.-$N_r$) curve is divided into a few zones based on its piecewise slopes. Five zones (Figure 5-5-b) proved to be adequate in the simulations carried out in this section. The permissible operating region comprises Zones I to III:

- **Zone I**: Slope $\leq -x_1$. In this zone, the power set-point can be increased at a relatively fast rate ($k_1$).

- **Zone II**: $-x_1 < $ Slope $\leq -x_2$. This zone corresponds to a rather flat segment of the power curve. The power set-point is increased at a slight rate ($k_2 < k_1$) to prevent the converter system from inadvertently overloading the turbine. A small value is recommended for $k_2$, as it would allow the power to be fine-tuned. A small $k_2$ could prevent undesirable set-point chatter around the maximum power point.
**Zone III:** \(-x_2 \leq \text{Slope} \leq 0\). This zone is a dead-band in the neighborhood of the peak available power. The set-point is maintained at a constant level by applying zero to the integrator in Figure 5-5-a.
• **Zone IV**: $0 < \text{Slope} \leq x_3$. In this zone, the turbine is starting to fall into the unstable region. The power set-point is decreased by applying a negative constant ($-k_3$) to the integrator stage.

• **Zone V**: Slope $> x_3$. Here if $P_{grid}^*$ is not reduced rapidly enough, the turbine may stall. The set-point is decreased at a faster rate ($-k_4 < -k_3$).

As a further protective measure, the MPPT mode can be disabled when turbine under-speed is detected, thus dropping the power set-point instantly to zero.

### 5.3.1.3 Parameter Selection and Performance Evaluation

Suitable values for parameters $x_1$-$x_3$ and $k_1$-$k_4$ for the above MPPT controller as well as the sampling rate were determined through emt-simulation. To consider an extreme condition, the rate of water velocity change was assumed to be $1 \text{ m/s}^2$. This figure seems to be higher than expected in real life. With this ramp time, the simulations indicated an upper-bound sampling period of $20\text{ms}$ for $P_g$ and $f_g$. Several simulations were conducted with different parameter values and sampling rates. The following MPPT parameters were selected based on those results, using trial and error:

- $x_1 = 0.05\text{kW/Hz}$, $x_2 = 0.03\text{kW/Hz}$, $x_3 = 0.01\text{kW/Hz}$.
- $k_1 = 10\text{kW/s}$, $k_2 = 0.1\text{kW/s}$, $k_3 = 10\text{kW/s}$, $k_4 = 50\text{kW/s}$.

The power tracking performance is demonstrated in Figure 5-6. The water velocity $V_w$ was changed from $2.27\text{m/s}$ to $2.06\text{m/s}$ and $2.48\text{m/s}$, according to the profile shown in Figure 5-6-a.
Figure 5-6: MPPT Performance. a) Velocity variations. b) Grid power $P_{grid}$. c) Transitions of the generator maximum power at different velocities.
The MPPT controller adjusts the grid power set-point $P_{\text{grid}}^*$ such that the converter transfers the maximum available power from the turbine-generator to the network at each water velocity $V_w$ (Figure 5-6-b).

Figure 5-6-c depicts the transition of the steady-state operating points at different water velocities. This is denoted by numbers 1 to 4. As a reference for comparison, the turbine power-vs.-speed characteristics at the test $V_w$ levels are shown as dotted curves.

These simulation results suggest that using the presented algorithm, the turbine-generator can be controlled to track the maximum available power without a feedback from the water velocity. Moreover, detailed specifications such as the turbine power coefficient profile, maximum $C_p$, etc. are not required.

### 5.3.2 Power Tracking Control Using Turbine Characteristics

The MPPT method explained in 5.3.1 seems to be suitable when little information is available on the turbine specification. If more information is known (i.e. the maximum power coefficient $C_{p_{\text{max}}}$ and its respective tip-speed ratio $\lambda_{\text{opt}}$), an alternative control method can be employed, which is easier to implement. This is adapted from one of the tracking techniques for controlling wind turbines ([63]-[65]). Here, similar to 5.3.1, a speed transducer is not required on the turbine-generator, which is desirable. The method is discussed below.

The tip-speed ratio $\lambda$ in (2-4) can be rearranged as follows:
\( \lambda = \omega_t \cdot R/V_w \Rightarrow V_w = \omega_t \cdot R/\lambda \) \hspace{1cm} (5-8)

In (5-8), \( V_w, \omega_t \) and \( R \) are the water velocity, the turbine angular speed and its radius, respectively. Replacing (5-8) for the water speed \( V_w \) in the turbine power equation (2-1) yields:

\[
P_t = 0.5 \cdot C_p \cdot A \cdot \rho_{\text{fluid}} \cdot (\omega_t \cdot R/\lambda)^3
\] \hspace{1cm} (5-9)

Assuming that the turbine has a fixed blade pitch angle, the optimal tip-speed ratio \( \lambda_{opt} \) is defined as the TSR at which the power coefficient \( C_p \) is maximum, as denoted in Figure 5-1. Hence:

\[
P_{t_{\text{max}}} = 0.5 \cdot C_{p_{\text{max}}} \cdot A \cdot \rho_{\text{fluid}} \cdot (\omega_t \cdot R/\lambda)^3 \Rightarrow
\]

\[
P_{t_{\text{max}}} = \left(0.5 \cdot C_{p_{\text{max}}} \cdot A \cdot \rho_{\text{fluid}} \cdot R^3/\lambda_{\text{opt}}^3\right) \cdot \omega_t^3
\] \hspace{1cm} (5-10)

The expression in the brackets is a constant. The turbine maximum power is proportional to its speed cubed. Due to this relationship, this control method is also referred to as \( k\omega^3 \) (or \( k\Omega^3 \)) control strategy [63].

Equation (5-10) indicates that using a feedback from its speed, the turbine can be controlled to operate at its maximum power. With a PMSG, the generator frequency is directly proportional to the turbine angular speed \( \omega_t \):

\[
\omega_t = (1/n) \cdot \left(4 \pi f_{g}/p\right), \quad n > 1
\] \hspace{1cm} (5-11)

where \( n, p \) and \( f_g \) are the gear increaser ratio, the PMSG pole number and its frequency. In the grid-connected mode, the grid power set-point \( P_{\text{grid}}^* \) can be chosen using (5-10) and (5-11), as given in (5-12):
\[ P_{\text{grid}}^* = \left( \frac{32 \cdot \pi^3 \cdot C_{p_{\text{max}}} \cdot A \cdot \rho_{\text{fluid}} \cdot R^3}{\lambda_{\text{opt}}^3 \cdot n^3 \cdot p^3} \cdot \eta \right) \cdot f_g^3 \cdot \eta < 1\]  
(5-12)

In order to avoid overloading, factors such as the losses on the mechanical drive-train and the power interface, etc. need to be accounted for. This is addressed by \( \eta \) in (5-12). With \( C_{p_{\text{max}}} \) and \( \lambda_{\text{opt}} \) given, the constant \( \kappa \) in (5-12) can be calculated. The power set-point is then determined based on the PMSG frequency measured by the generator-side PLL.

The block diagram of the turbine controller is shown in Figure 5-7. The rate limiter ensures that the set-point increases at an acceptable rate. The MPPT strategy presented in 5.3.1 had a ‘trial-and-enhance’ nature. In contrast, this control technique is based on a feed-forward path.

The performance of the scheme is demonstrated in the simulation results shown in Figure 5-8 and Figure 5-9. The same turbine parameters used in 5.3.1 were applied.
here (i.e. $C_{p_{max}}=0.47$ and $\lambda_{opt}=1.8$). With an efficiency of 98% for each of the power converters (from datasheet: at full load and a switching frequency of 6 kHz) and a typical efficiency of about 80% for the mechanical drivetrain, the overall efficiency is assumed to be $\eta=0.98^2 \times 0.8 \approx 0.77$. So, the upper bound of the $k\omega^3$ controller in (5-12) is $\kappa \approx 0.0092$ kgm$^2$. To ensure that the turbine operates on the right side of the $C_p-\lambda$ curve, a smaller $\kappa$ is selected. In the following simulations, $\kappa$ is set to 0.006kgm$^2$. Also, $P_{grid}^*$ increase rate is limited to 0.01kW/s.

The water velocity $V_w$ is changed from 2.27m/s to 2.06m/s and 2.48m/s, according to the profile plotted in Figure 5-8-a. The PMSG frequency variations are plotted in Figure 5-8-b. The grid power at different water speed levels is given in Figure 5-9-b.
Figure 5-9: Performance if the k\(\omega^3\) power control scheme. 

a) Velocity variations.

b) Grid power \(P_{\text{grid}}\).

c) Transitions of the generator maximum power at different velocities.
Figure 5-9-c shows the transition of the steady-state operating points 1 to 4 at different water velocities. The locus is denoted by numbers 1’ to 4’. As a reference for comparison, the turbine power-vs.-speed characteristics at the test $V_w$ levels are shown as dotted curves.

**5.3.3 Concluding Remarks**

In addition to the techniques presented in this chapter, other algorithms are also employed to control wind turbines such as those based on the turbine $C_p$-$\lambda$ curves [66]. In those methods, for instance, the turbine tip-speed ratio $\lambda$ is calculated using by measuring wind velocity and turbine speed. The calculated $\lambda$ along with the turbine blade pitch angle (for variable-pitch turbines) are applied to a look-up table to determine the instantaneous turbine $C_p$ and subsequently, power set-point. This, however, does not seem to be suitable for controlling hydrokinetic plants since it requires sensors.

Neither of the tracking methods explained in this chapter requires a feedback from the flow velocity, or needs a turbine speed transducer. This is an advantage in hydrokinetic applications as sensorless methods are desirable.

When little information is available on the turbine specification, the MPPT method explained in 5.3.1 appears to be a suitable solution. The power set-point rate parameters ($k_1$ to $k_5$ in Figure 5-5-c) can be adjusted using the measured slope $\Delta P_t/\Delta f_g$ during field commissioning.
The method based on the turbine characteristics ($k\omega^3$) discussed in 5.3.2 appears to be straightforward to implement. The power set-point is determined based on the PMSG frequency measured at the generator-side converter.
Chapter 6

Potential Use of Kinetic Turbines in Kinetic Farms

6.1 Introduction

Utilization of multiple kinetic turbine-generators in a kinetic farm increases the overall harnessed energy from a stream. In a kinetic farm, several turbines are installed at different locations in a river, forming a network of kinetic turbine units. This also improves the reliability of the hydrokinetic plant as loss of one unit will not necessarily interrupt the supply of power to the load. That is particularly critical in islanded systems.

In a kinetic farm, each turbine may be subject to a different water velocity. Hence, the power produced by each generator in the Farm will be different and should be regulated before the units can be interconnected. This chapter introduces a few approaches for constructing multi-turbine hydrokinetic plants.

6.2 General Control Considerations

A kinetic farm may be connected to the utility grid, may supply an islanded load, or can supplement the generation in a micro-grid with different types of generation. When integrated with the utility network, it is normally desirable to transfer the maximum available power from individual turbines to the ac system. In this case, turbine control techniques such as those explained in chapter 5 (MPPT and $k\omega^3$
control) can be employed. Control of each turbine will be independent of the others. The output power from each unit depends on the water velocity at the location where the turbine is installed.

In islanded operation, the kinetic farm should supply the ac load with regulated voltage and frequency. When supplementing the generation in a micro-grid, the load-side converters should employ frequency and/or voltage droop control [66] in order to emulate the behavior of conventional synchronous generators (a kinetic farm formed by inverter units parallel on an ac bus can also be considered a micro-grid). Thus, power is automatically shared among the generating units in the micro-grid and the kinetic farm.

Flow velocity fluctuations in a river may ‘travel’ along the current; i.e. flow variations at a turbine installed upstream may appear at the turbine installed downstream after a certain delay. This may provide predictability, such that a main plant controller can predict the availability of power by monitoring the speed at the upstream turbine location.

These control aspects will be discussed in the following sections.

6.3 Possible Interconnection Methods

In this section, it is assumed that the kinetic farm only includes units with PMSGs. Schemes using induction generators are not considered in this thesis.

Two options can be considered for interconnecting kinetic turbine units:

- Power interfaces connected on a common dc link
• Power interfaces interconnected at the ac side

The two options are explained below.

6.3.1 Interconnection at the DC Links

In this configuration, the controlled rectifiers are connected to a common dc bus. The dc bus is interfaced with the ac system through one or more inverters as indicated in Figure 6-1. The controlled rectifiers can be connected to the inverter via dc cable links. Normally, each converter module is equipped with its own dc capacitor, as shown in that figure.

![Interconnection of multiple kinetic turbine converters via dc cables on a common dc bus](image)

Multiple inverters (e.g. Inverter #2 in Figure 6-1) may have to be used if the rated power of a single inverter cannot handle the total power that needs to be transferred to the ac side. Such a configuration also provides redundancy and helps improve the reliability of the power interface system.
At least, one of the converters should regulate the dc voltage on the common bus. If more converters are involved in dc voltage regulation, the normal approach is to use a dc voltage droop control. This ensures proper power sharing between the dc regulators. This method will be explained in 6.3.1.1.

When a kinetic farm is connected to the utility grid, dc voltage control can be relegated to the grid-side converter(s). The rectifiers can then operate in the active power control mode. Thus, the turbines are controlled to harness the maximum power available from each unit at different flow levels.

In islanded or micro-grid support mode, the inverter cannot be used for dc voltage regulation, since an external source may not exist on the ac side. Therefore, at least one of the rectifiers should maintain the dc voltage. Operation of multiple rectifiers based on dc voltage droop method can help share power among the converters, as explained below.

6.3.1.1 DC Voltage Droop Control Strategy

In Figure 6-2, two dc voltage sources are connected in parallel and supply a common load $R_L$. They have equal open-circuit voltages ($V_{dc}$), but different internal resistances ($R_1$ and $R_2$). The total load current $i_L = i_1 + i_2$ is shared by the voltage sources based on the current divider rule, according to (6-1):

$$i_1 = i_L \cdot \frac{R_2}{R_1 + R_2}$$
$$i_2 = i_L \cdot \frac{R_1}{R_1 + R_2}$$

(6-1)

The output voltage $V_L$ will be:
\[ V_L = V_{dc} - i_1 R_1 = V_{dc} - i_2 R_2 \]  

(6-2)

Equations (6-1) and (6-2) imply that the voltage ‘droop’ caused by the resistances \( R_1 \) and \( R_2 \) balances the load distribution among the sources, such that a larger portion of the load is taken over by the source with the smaller resistance (i.e. higher capacity). This can be generalized for more than two parallel voltage sources.

Introducing a physical resistance to parallel rectifiers, of course, would not be advisable as it is associated with resistive losses. However, a control system can be designed to provide an output dc voltage that emulates the resistances in (6-2) using appropriate droop factors. Thus, controlled dc voltage sources can be connected in parallel to supply a common load. The voltage set-points for each voltage source can be specified similar to (6-2). The effect of an internal resistance for each of the parallel controlled sources is emulated by a droop factor \( R \).

6.3.1.2 Parallel VSCs With DC Droop Controllers in a Kinetic Farm:

Islanded Mode

In islanded mode, the inverter supplies regulated ac voltage. For a given load, the inverter transfers constant power from the dc link to the ac bus. The inverter dc current is represented by \( I_{\text{Load}} \) as depicted in Figure 6-3. The dc voltage is
maintained by the rectifiers. For simplicity, only two parallel turbine-generators and rectifiers are considered. But the concept can be applied to more units. In this example, the ac side load is considered as a fixed impedance. Hence, assuming that the inverter maintains a fixed ac-side voltage, it corresponds to a constant-power load. This means that \( I_{\text{Load}} \) will change slightly as \( V_{dc} \) changes, so that the product \( V_{dc}I_{\text{Load}} \) remains constant.

Figure 6-3: Two kinetic turbines supplying a load shared on a common dc bus

As shown in 4.2.4.1.a, the dc-bus voltage of a VSC can be regulated by controlling its \( d \)-axis current \( i_d \). This will control the power imported to, or exported from, the dc bus to keep the dc capacitor’s voltage constant. Therefore, the \( d \)-axis current \( i_d \) can represent the VSC’s dc current in the dc voltage droop controller. This method is depicted in the block diagram of Figure 6-4, where \( V_{dc-ref} \) is the desired dc voltage reference. The actual dc voltage set-point \( V'_{dc} \) is obtained in a manner similar to (6-2). Here, \( R_d \) is the droop factor. An advantage if this method is that an additional sensor is not required for dc current measurement.

For multiple VSC-based rectifiers connected in parallel on a common dc bus, the dc voltage set-point \( (V'_{dc}) \) for each VSC is determined similar to the scheme in Figure 6-4. The portion of the power supplied by each converter is determined by its
respective droop factor $R_d$. The droop factor $R_d$ for each rectifier in the Farm can be specified according to the rated power of the converter and/or the PMSG. If the rated power levels are equal, identical droop factors can be applied.

![DC voltage droop control using the PMSG $d$-axis current $i_d$](diagram)

For a constant load, each rectifier maintains the dc-link voltage $V_{dc}$ at the desired set-point $V_{dc}^*$ by absorbing power from its generator. It can be shown that the proposed droop control with a feedback from the generator active current $i_d$ allows for ‘adjustable’ droop characteristics on the dc side. Assuming identical droop factors, the dc voltage for each rectifier in Figure 6-4 is regulated by the proposed droop controller as follows.

For easier demonstration, two parallel rectifiers are considered. The common dc voltage $V_{dc}$ is obtained from the droop characteristics in Figure 6-4:

\[
\begin{align*}
\text{Rectifier 1: } V_{dc} &= V_{dc-ref} - R_d \cdot i_{d1} \\
\text{Rectifier 2: } V_{dc} &= V_{dc-ref} - R_d \cdot i_{d2}
\end{align*}
\]

(6-3)

If converter losses are neglected, the power transferred from each rectifier’s ac side to the dc bus will be equal. Therefore:

\[
\begin{align*}
P_{dc1} = P_{ac1} &\Rightarrow V_{dc} \cdot I_{dc1} = 1.5 \times V_{d1} \cdot i_{d1} \Rightarrow i_{d1} = \frac{1.5 \cdot V_{dc}}{V_{d1}} \cdot I_{dc1} \\
P_{dc2} = P_{ac2} &\Rightarrow V_{dc} \cdot I_{dc2} = 1.5 \times V_{d2} \cdot i_{d2} \Rightarrow i_{d2} = \frac{1.5 \cdot V_{dc}}{V_{d2}} \cdot I_{dc1}
\end{align*}
\]

(6-4)
In (6-4), $v_{dl}$ and $v_{d2}$ are the $d$-axis voltages at each rectifier’s ac side. Since each rectifier is locked onto its respective ac phase voltage, the $q$-axis voltages are zero.

From (6-3) and (6-4):

\[
\begin{align*}
\text{Rectifier 1:} & \quad V_{dc} = V_{dc-ref} - R_d \cdot 1.5 \cdot \frac{V_{dc}}{v_{d1}} \cdot I_{dc1} \\
\text{Rectifier 2:} & \quad V_{dc} = V_{dc-ref} - R_d \cdot 1.5 \cdot \frac{V_{dc}}{v_{d2}} \cdot I_{dc2}
\end{align*}
\]

The equations in (6-5) indicate a drooping relationship between the dc voltage $V_{dc}$ and the rectifier dc currents $I_{dc1}$ and $I_{dc2}$. The effective dc droop factor ($R_{dc}$) for each converter is a function of its respective ac voltage. For easier demonstration, the equations in (6-5) can be linearized as shown below:

\[
\begin{align*}
\text{Rectifier 1:} & \quad V_{dc} \approx V_{dc-ref} - R_{dc}(v_d) \cdot I_{dc1} \\
\text{Rectifier 2:} & \quad V_{dc} \approx V_{dc-ref} - R_{dc}(v_d) \cdot I_{dc2}
\end{align*}
\]

With identical water velocities at both turbines, the generators operate at equal speeds, thus producing equal voltages. Hence, the effective dc droop factors in (6-7) will be identical. As a result, the rectifiers share the load equally, as shown in Figure 6-5-a. When a turbine slows down due to a drop in the flow, its respective PMSG
voltage will decrease. Therefore, the effective dc droop in (6-6) will increase for its rectifier, thus reducing the portion of the load supplied by that turbine. This is presented in Figure 6--b. An increase in flow will have an opposite impact.

Hence, power distribution among multiple parallel rectifiers is achieved automatically at different load levels and flow speeds. This will be demonstrated through an example later in this section.
Limiting $i_{dr,max}^*$ to Prevent Stalling

In order to avoid turbine stalling, the power absorbed from the generator must be limited. A proposed method is presented in Figure 6-6. The maximum power available from the turbine at different water velocities can be obtained from a turbine control algorithm such as a $k\omega^3$ controller as explained in 5.3.2. When the turbine specifications (namely the maximum coefficient of power $C_{p,\text{max}}$ and the corresponding tip-speed ratio $\lambda_{\text{opt}}$) are known, the turbine-generator maximum power $P_{g,\text{max}}$ can be obtained from (5-12). It was shown in 5.3.2 that the PMSG frequency $f_g$ could be used for this purpose. Using this value and the PMSG voltage $d$ and $q$ components ($v_{dr}$ and $v_{qr}$ in Figure 4-11), the maximum acceptable value for the current reference $i_{dr}^*$ can be determined as:

$$i_{dr-max}^* = \frac{P_{g-ma}}{3/2 \times v_{dr}} \quad (6-8)$$

In order to avoid instability, the rate of change for $i_{dr-max}^*$ is limited. The converter rated current is applied in the final stage in Figure 6-6 as an additional limit. This value ($i_{dr-max}^*$) is applied to the dc voltage regulator’s PI controller as the upper limit.
The performance of this control scheme is demonstrated in the following simulation example for two kinetic turbines.

The turbine-generators and converters in Figure 6-3 have parameters and specifications identical to those of the unit explained in chapter 4 and chapter 5. At no-load, the converters maintain the dc bus voltage at 985 V. Both converters have a droop factor of \( R_d = 0.1 \, \Omega \).

**Performance of the dc Voltage Droop Controller**

The performance of this scheme is presented in Figure 6-7. The plants are about 12.5 m apart along the stream. Assuming a flow velocity of 2.5 m/s, any water speed change applied to turbine 1 (upstream) is observed by turbine 2 (downstream) after about 5 s. Larger delay times may exist if the turbines are further apart (e.g. 50 m or 100 m, etc.); but the shorter distance required shorter simulation time. In principle, this does not have a significant impact on the performance of the scheme, as each turbine unit is controlled autonomously.

The flow speed varies at turbine 1 according to the profile shown Figure 6-7-a. Turbine 2 observes those changes after a 5-second delay. The total load connected to the dc bus is 20 kW. As long as both turbines are exposed to the same flow levels, they deliver equal portions of the total load (i.e. 10 kW) as can be observed in Figure 6-7-c.
Figure 6-7: DC voltage droop control performance for two kinetic turbines operating in parallel, supplying an islanded load. a) Water velocity variations at each turbine. b) Total load. c) Power levels delivered by each generator. d) Generator frequencies. e) DC link voltage.

Once the velocity at turbine 1 rises, the turbine speed increases, leading to an increase in the PMSG voltage and a drop in its current. Hence, the effective droop is reduced, and turbine 1 picks up a larger portion of the load. This relieves turbine 2
which has a lower capacity due to slower flow. When the water speed at turbine 1 becomes less than the velocity at turbine 2, the latter takes over a larger share of the total load. The PMSG frequencies and the dc voltage are shown in Figure 6-7-d and Figure 6-7-e, respectively.

**Effect of Load Disturbances**

Step changes are applied to the load between $t=4s$ and $t=6s$ (as in Figure 6-7-c), from 20kW to 30kW, from 30kW to 35kW, and from 35kW to 20kW, respectively. The converters successfully maintain the dc voltage close to the set-point (985V). The added load is appropriately shared by the two units.

In Figure 6-7-e, the dc voltage rise following the load drop is within the converter dc over-voltage limit. However, as explained in 4.2.4.3, it may be necessary to add a dc chopper to the dc bus to dissipate the excess energy in order to avoid unacceptable over-voltages caused by load rejection. A dc chopper was modeled in the simulations, but was not activated following the abrupt load drop in Figure 6-7-b. If extensive simulations indicate that a chopper would not be necessary, it can be removed from the design.

**Performance of the Stall Protection Activated by Low Flow Conditions**

In case of low flow, the control method explained above (in Figure 6-6) will limit the active current absorbed from the PMSGs. This leads to a drop in the dc voltage, as the rectifiers cannot supply the dc link with sufficient energy to maintain the
capacitor voltage. Although turbine stalling will be avoided, the inverter cannot supply ac voltage at the desired level. Therefore, appropriate under-voltage load shedding will have to be considered in the protection system. Loads with lower priority need to be tripped in order to preserve the power balance between demand and available generation. This aspect was not considered in this thesis. But it will be shown through an example how load shedding can help prevent under-voltage.

In Figure 6-8, the two-turbine system used in the previous simulation supplies a total load of 30 kW. As shown in Figure 6-8-a, the water speed is about 2.5 m/s at both turbines and the two generators are loaded equally (Figure 6-8-b).

When the speed drops to 2.1 m/s at turbine 1, the load is redistributed between the two generators through dc droop control. Generator 2 supplies about 18 kW and the output of generator 2 is reduced to about 12 kW. When the water speed decreases at turbine 2, the current limiter on rectifier 2 reduces its respective maximum current reference $i_{dr-max}$ and the output of this unit drops. Once the total power available from the two turbine-generators cannot meet the load demand, the dc voltage is reduced as shown in Figure 6-8-c. This situation is indicated by the dotted line in Figure 6-8.
Figure 6-8: Performance of the stall protection scheme when subjected to a drop in water speed.

a) Water velocities at measured at each turbine. b) Load and generator power levels. c) dc bus voltage. d) Generator frequencies. e) Active current limits ($i_{d\text{-max}}$) for each rectifier.
**Stall Protection Activated by Load Increase**

The PMSG frequency variations are plotted in Figure 6-8-d. The outputs of the two current limiters (i.e. $i_{dr-max}$ for the two rectifiers) are given in Figure 6-8-e. These results demonstrate that turbine stall is prevented. The turbine outputs are limited to the maximum power available at the new flow conditions.

A similar situation can occur following a load increase. The simulation results in Figure 6-9 present the performance of the stall prevention scheme following a +10 kW step change in the load. Prior to the load increase, the two PMSGs supply a 35 kW load. As before, the water speed at turbine 1 is initially the same as the speed at turbine 2, but reduces to 2.3m/s as shown in Figure 6-9-a. The controllers respond to this change and the load distribution between the turbines is readjusted. At about $t=2.5$ s, the dc load increases to 45 kW (Figure 6-9-b). It can be observed in Figure 6-9-e that the current limiter on rectifier 2 reacts as only about 38 kW is available from the two turbine-generators at the given flow conditions. Hence, the dc voltage cannot be maintained at 985 V any longer, as shown in Figure 6-9-c. The current limiters successfully prevent the turbines from stalling as shown by the PMSG frequency variations given in Figure 6-9-d. The steady-state dc under-voltage can be avoided by a load shedding strategy, similar to the results shown earlier in Figure 6-10. The under-voltage can be avoided by adequate load shedding. This is shown in Figure 6-10 and explained below.
Figure 6-9: Performance of the stall protection scheme when subjected to increase in the dc load. a) Water velocities at measured at each turbine. b) Load and generator power levels. c) dc bus voltage. d) Generator frequencies. e) Active current limits ($i_{d,max}$) for each rectifier.
Load shedding to Prevent Under-voltage

In Figure 6-10, the same scenario explained above was applied to the two-turbine system. The dc voltage was used as the monitored parameter for protection.

As a simple under-voltage load shedding strategy, about 27% of the load was ‘shed’ once the dc voltage dropped below 900 V (0.91 p.u. on a 985 V base). It can be observed in Figure 6-10-d that the dc voltage drop caused by stall protection is prevented. The dc link voltage is recovered to an acceptable level of 960 V in steady state. At this dc voltage, the ac voltage at the load terminals can be adjusted to 588 V (rms) with no over-modulation. This voltage is equivalent to 0.98 p.u., which is above the acceptable under-voltage limit of 0.95 p.u. In a practical scheme, the load shedding strategy would involve time delays to prevent false load tripping due to transient under-voltages. The loads will also have to be prioritized such that unimportant loads would be tripped in the first load shedding stage(s).

6.3.1.3 Parallel VSCs With DC Droop Controllers in a Kinetic Farm:

Grid-connected Mode

When multiple rectifiers share a common dc bus, it seems more convenient to operate the grid-side converter as the dc voltage controller. The PMSG-side converters can operate in active power control mode. If multiple grid-side VSCs are used in parallel on the dc bus, dc voltage droop control can be introduced to their controls, similar to the method explained in 6.3.1.2.
Figure 6-10: Performance of under-voltage load shedding protection. 

- **a)** Water velocities at measured at each turbine.
- **b)** Load and generator power levels. 
- **c)** dc bus voltage. 
- **d)** Generator frequencies. 
- **e)** Active current limits ($i_{dr-max}$) for each rectifier.

The power set-point applied to each PMSG-side converter (rectifier) is determined from a turbine control strategy, such as P&O MPPT (explained in 5.3.1) or $k\omega^3$. 

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(explained in 5.3.2). The power transferred to the grid will be the sum of the ‘maximum’ power levels available from each turbine at different flow conditions. The simulation results in Figure 6-11 demonstrate this operation mode.

The two-turbine system of 6.3.1.2 is connected to the grid, as shown in Figure 6-1.

A single inverter (grid-side converter) links the common dc link with the grid. The
grid voltage and frequency are 600 V and 60 Hz, respectively. The dc voltage set-point in this set of simulations is selected to be 990 V, which is maintained by the inverter. The power tracking algorithm explained in 5.3.2 \((k\omega^3)\) is used to control the PMSG-side converters. The water speed at each turbine varies according to Figure 6-11-a. The \(k\omega^3\) controller at each rectifier adjusts the power set-point based appropriately to capture the maximum power from the flow, while ensuring stable turbine operation. This is shown in Figure 6-11-b. The total power delivered to the grid is also plotted in this figure. It can be noticed that the total output power is the sum of the powers produced by individual turbine-generators. The grid power is slightly lower than the total power absorbed from the two PMSGs, due to losses. The inverter maintains the dc voltage at 990 V, as shown in Figure 6-11-c. The PMSG frequency variations are shown in Figure 6-11-d.

### 6.3.2 Interconnection on the AC side

In this configuration, the kinetic turbine power interfaces are connected to the ac system as depicted in Figure 6-12, similar to what is done for conventional generation. Each turbine-generator and its respective power interface represent an ac ‘generator’. Similar to the modes explained in 6.3.1, the units may operate in grid-connected mode, or they may have to supply an islanded load. Supplementing generation in a micro-grid falls in the latter category.

When connected to the grid, the kinetic turbines normally transfer the maximum energy captured from the flow using a turbine control scheme. The power delivered
to the grid will be the total power harnessed by individual turbines in the kinetic farm. This is similar to the cases shown in Chapter 5 for individual kinetic turbine units. Therefore, this mode of operation is not demonstrated in this section.

Figure 6-12: Interconnection of multiple kinetic turbine power interfaces at the ac system side.

In an ac grid when several generators are connected in parallel, frequency droop control is used for distributing the load’s active power among those sources [21]. Reactive power demand by the system load is also shared by the sources through voltage droop control [66],[69]. These control methods have been discussed in detail in the literature (e.g. [66]-[70]). They can be applied to ac systems supplied by multiple inverters connected in parallel. Thus, an inverter emulates the performance of a conventional synchronous generator with speed governor and automatic voltage regulator (AVR). This concept is explained below.

6.3.2.1 Frequency and Voltage Droop Control

Two typical frequency and voltage droop characteristics are shown in Figure 6-13 for an ac voltage source. In Figure 6-13-a, the frequency drops with active power. This function is used in conventional governor systems [21]. At no-load, the source
frequency is at $f_0$, which can be the nominal frequency (i.e. 1 p.u.). At full load ($P = P_{\text{max}}$), the frequency drops to $f_{\text{fl}}$. The slope of the frequency-power characteristics is referred to as the frequency droop $R_f$. For example, with a typical frequency droop of 5%, the source frequency reduces from 1 p.u. at no load to 0.95 p.u. at full load. For a 60-Hz system, this represents a 3-Hz reduction in the source frequency at full load. As shown later in this section, this prevents parallel sources from fighting for a stable operating condition.

In a similar manner, Figure 6-13-b demonstrates a typical voltage droop relationship between voltage and reactive power. The slope of the line in this figure is referred to as the voltage droop $R_v$. For a zero reactive power demand, the voltage set-point is $V_0$, which can be the nominal ac voltage (i.e. $V_0 = 1$ p.u.). The ‘drooping’ characteristics towards the capacitive source region helps coordinate the reactive supply/absorption among parallel sources as demonstrated later in this section.

**Frequency Droop Control**

The frequency-vs.-active power ($f$-$P$) and voltage-vs.-reactive power ($V$-$Q$) characteristics in Figure 6-14 can be written as:

$$
\begin{align*}
    f &= f_0 - R_f \cdot P \\
    V &= V_0 - R_v \cdot Q
\end{align*}
$$

These control schemes are explained for two inverters connected in parallel and supplying a common islanded ac load, as depicted in Figure 6-14. The concept can be easily applied to more parallel inverters, or inverters connected in parallel with conventional generators.
The two inverters supply the load with active and reactive power, such that $P_{\text{Load}} = P_1 + P_2$ and $Q_{\text{Load}} = Q_1 + Q_2$. Inverter 1 has frequency and voltage droop factors of $R_{f1}$ and $R_{v1}$, respectively. The frequency and voltage droop factors for Inverter 2 are $R_{f2}$ and $R_{v2}$, respectively. With a methodology similar to (6-1) and (6-2), it can be shown that the power sharing ratio between the two inverters is inversely proportional to their respective frequency droops; i.e.:

$$\frac{P_1}{P_2} = \frac{R_{f2}}{R_{f1}}$$  \hspace{1cm} (6-10)

Hence:

$$\begin{cases} 
    P_1 = \frac{R_{f2}}{R_{f1} + R_{f2}} \times P_{\text{Load}} \\
    P_2 = \frac{R_{f1}}{R_{f1} + R_{f2}} \times P_{\text{Load}}
\end{cases}$$  \hspace{1cm} (6-11)
According to (6-11), the inverter with a smaller frequency droop takes over a larger portion of the common load. For example, if inverters 1 and 2 are rated at 60 kW and 120 kW, respectively, a 3% frequency droop will represent 0.03 Hz/kW for Inverter 1 and 0.015 Hz/kW for Inverter 2. From Figure 6-15, it can be observed that to supply a 120-kW load, Inverters 1 and 2 provide 40 kW and 80 kW, respectively. The steady-state frequency at this load is 58.8 Hz.

Similar to (6-10), the inverter reactive power shares are inversely proportional to their voltage droop factors:

\[
\frac{Q_1}{Q_2} = \frac{R_{v2}}{R_{v1}}
\]  

(6-12)

Therefore:

\[
\begin{align*}
Q_1 &= \frac{R_{v2}}{R_{v1} + R_{v2}} \times Q_{Load} \\
Q_2 &= \frac{R_{v1}}{R_{v1} + R_{v2}} \times Q_{Load}
\end{align*}
\]

(6-13)

Figure 6-15: Frequency droop control between two parallel ac sources
For parallel-connected inverters operating in islanded mode, it is common [70] to run one of them as a Master inverter [70].

**Control of the Master Inverter:** The Master inverter produces a voltage with regulated magnitude and frequency [66] to establish a basis for a micro-grid. It operates based on frequency droop. Upon a change in the system load, the Master inverter responds by varying the frequency according to its droop factor $R_{f\text{-master}}$ and the characteristics in (6-9). The block diagram in Figure 6-16 depicts the calculation of the inverter output frequency. The block outlined as ‘frequency droop controller’ provides the frequency reference $f$, which is applied to a voltage-controlled oscillator (see Figure 4-13) to produce the reference frame angle $\theta$. This angle is used for generating the voltage waveforms in the islanded mode, as shown in the corresponding sub-block in Figure 4-11. The frequency reference $f$ is limited between $f_{\text{max}}$ and $f_{\text{min}}$.

The base frequency can be slowly adjusted through a steady-state frequency controller as depicted in Figure 6-16, in order to return the steady-state frequency to the nominal frequency (i.e. 50 Hz or 60 Hz). This is not considered in the simulations performed for this section.
Control of the Slave Inverters: Other inverters (Slave inverters) are locked onto the voltage supplied by the Master inverter using their respective phase-locked loops (PLLs). They operate in power control mode. The power reference for the \( i \)-th Slave inverter \( (P_{ref,i}) \) is calculated using its respective frequency droop \( R_f \) and the deviation of the frequency \( f \) from the nominal frequency \( f_0 \), as shown in (6-14):

\[
P_{ref,i} = \frac{f_0 - f}{R_f} \quad (6-14)
\]

The ac system frequency \( f \) is measured by each inverter’s PLL.

Voltage Droop Control

The Master inverter also controls the voltage magnitude according to the voltage droop characteristics in (6-9). The reactive power set-point in the \( i \)-th Slave inverter \( (Q_{ref,i}) \) is determined from its respective voltage droop factor \( R_v \) and the deviation of the ac voltage \( V \) from the nominal no-load voltage \( V_0 \):

\[
Q_{ref,i} = \frac{V_0 - V}{R_v} \quad (6-15)
\]

The ac voltage is measured by each slave inverter. If the inverters are connected to an existing micro-grid with conventional generator-governor systems, all of them may operate in power control mode as Slave inverters, based on (6-14) and (6-15).
Incorporating the Effect of Variable Available Power

The values for the frequency (and voltage) droop factors for each converter should be chosen based on the converter’s rated power. However, in renewable-energy-based generation, such as a kinetic farm, the power available from the energy resource varies, and can be less than the rated power of the inverters. Each kinetic turbine may experience a different flow velocity and hence, will have a different generation capability from other turbines in the farm. This seems to necessitate a dynamic reallocation of frequency droop factors among the kinetic farm inverters. In this manner, the turbines exposed to higher water speeds would take over a larger portion of the overall load. Thus, the risk to overload turbines running at low flow can be reduced.

As shown in 6.3.1.2, the PMSG $d$-axis current ($i_{dg}$) could be used in the dc voltage droop controller. This allows for automatically adjusting power distribution among the turbines in a kinetic farm, when they operate at different flow conditions. A similar concept can be applied in the ac interconnection scheme. The rectifiers in the farm operate as dc voltage controllers. When a load is applied to the system, the Master inverter absorbs power from its dc link, thus loading its turbine-generator. Similar to the discussion in 6.3.1.2, if the flow varies under a constant load, the product $i_{dg}.R_{f\text{-master}}$ will change, leading to a change in the droop characteristics.

Slave inverters lock onto the ac voltages at their own busbars. Hence, they follow the frequency variations initiated by the Master inverter’s frequency droop characteristics as there is only one system frequency. Each slave inverter then regulates its own power set-point.
Neglecting the converter losses, the power absorbed from each PMSG ($P_g$) by its rectifier is equal to the power delivered to the ac system by the inverter ($P_{grid}$). Here $P_{grid}$ refers to the power delivered to the ac system, which can be considered a micro-grid. Using the variables shown in Figure 4-11, this can be written as:

$$P_{grid} \approx P_g = \frac{3}{2}(i_{dg} \cdot v_{dr} + i_{qg} \cdot v_{qr})$$

(6-16)

In (6-16), ($i_{dg},i_{qg}$) and ($v_{dr},v_{qr}$) are the PMSG’s $d$- and $q$-axis currents and voltages, respectively. The rectifier’s PLL aligns the $d$ axis on the PMSG’s phase A voltage, and hence, $v_{qr}$ is zero. Therefore:

$$P_{grid} \approx 1.5 \cdot i_{dg} \cdot v_{dr}$$

(6-17)

To maintain consistency with the droop control in the Master inverter, the characteristics in (6-14) is modified to provide the reference for the PMSG active current $i^*_{dg}$. This allows the Slave droop factors ($R_{fi}$) to be in the same scale as the Master droop $R_{f-master}$ in Figure 6-16. The frequency droop strategy in the Slave inverter(s) is shown by the block diagram in Figure 6-17. The ac system frequency $f_i$ is measured by the inverter’s PLL. The deviation from the nominal (no-load) frequency $f_0$ is divided by the Slave inverter’s droop factor $R_{fi}$ to provide the PMSG $d$-axis current reference $i^*_{dg}$. The grid power reference $P^*_{grid}$ is calculated based on (6-17). In this controller, the generator $d$-axis voltage $v_{dr}$ has an effect similar to $i_{dg}$ in the Master inverter. The generator voltage follows its speed changes caused by water speed variations. According to the current directions shown in Figure 4-11, a negative set-point $P^*_{grid}$ represents the power injected by the inverter to the load.
side. The upper band is limited to zero to avoid absorbing power from the ac system in case of over-frequency (e.g. following a load shedding, etc.).

Figure 6-17: Frequency droop controller in the Slave inverter(s).

**Overall Performance of the Frequency Droop Control**

Simulations were performed on a two-inverter interconnection supplying an islanded load. The concept is easily applicable to more than two inverters, or a combination of conventional generation and kinetic turbines. The system shown in Figure 6-12 was modeled with the component parameters used in the examples presented in Chapter 5 and section 6.3.1.2. Inverters 1 and 2 were configured as the Master and Slave inverters, respectively. The inverters supply a 600 V load at 60 Hz. The dc link voltage in this set of simulations was selected to be 1 kV.

A typical frequency droop factor of 5% [21] was applied to both inverters. Assuming a rated current of 100 A (peak) for each inverter, this value corresponds to 0.03 Hz/A. Only the performance of the frequency droop controller is demonstrated here as a new strategy. AC voltage droop control is extensively covered in the literature, including in [66]-[70], and is not discussed in this section.

The test described below covers a few events, such as water velocity fluctuation and load change. Initially, both turbines operate under similar flow conditions, with a
water velocity of 2.5 m/s. The inverters supply a 20-kW load. The load is shared between the two units almost evenly. When the water speed at turbine 1 (Master) drops from 2.5 m/s to 2.1 m/s, the turbine output is reduced. This reduction is compensated by an increase in the power from the Slave inverter.

**Impact of Water Velocity Fluctuations:** The water speed decrease then reaches turbine 2, leading to a reduction in the Slave inverter’s output. The Master inverter starts to take over until the load is shared evenly between the two units. The flow then increases at turbine 1 from 2.1 m/s to 2.5 m/s. Master inverter raises its output and relieves the loading on inverter 2.

**Impact of Load Disturbance:** Finally, when the speed at turbine 2 reaches 2.5 m/s, a 5 kW step change is applied to the load from 20 kW to 25 kW. This increase is distributed almost evenly between the two units.

A slight difference is observed between the inverter outputs powers when the turbines operate under identical flow conditions. The power delivered by the Slave converter is about 10% to 15% more than that of the Master inverter. There are a few reasons for this difference in the simulation results:

- The PLLs in the two rectifiers can have small (and different) tracking errors. This can lead to a small error in obtaining the PMSGs’ $d$-axis currents.
- On the ac load side, fine-tuning may be required in the Slave inverter’s PLL to improve the accuracy of the detected ac system frequency $f_1$. A small mismatch between the PLL output $f_i$ and the actual ac frequency can cause a small error in the power set-point $P^*_{grid}$. 
The technique described in 6.3.1.2 for stall protection can be applied to the rectifiers in this scheme. The dc voltage droop path in Figure 6-6 should be disabled by applying a zero dc droop factor $R_d$. The performance will be similar to the results shown in Figure 6-8 and Figure 6-9. An appropriate load shedding scheme (under-frequency [36] and/or under-voltage) needs to be implemented to prevent imbalance between generation and demand. This is outside the scope of this work.

In dynamic conditions or under light load conditions, a drop in the system load may lead to over-frequency, as generation may temporarily exceed the load.

A dump (ballast) load in the form of a variable resistor bank ([71],[72]) may be required to absorb the excess generation until the inverter restores the system frequency. In light load conditions when the power available from the flow is not used by the ac system loads, the resistive dump load can be continuously turned on and the dissipated energy can be used for heating purposes.

6.4 Concluding Remarks

This section presented two feasible configurations to form kinetic farms using multiple turbines. It was assumed that each turbine unit would use an electronic power interface between its respective generator and the ac load.

- If the generator-side converters are linked on a common dc bus, dc voltage droop control can be used for sharing the load power among multiple turbine-generators units. The performance of this scheme and a stall protection strategy were demonstrated through emt simulation results.
Figure 6-18: Performance of the frequency droop controller. a) Water speed fluctuations at each turbine. b) Load power and inverter outputs at different turbine speeds and load levels. c) PMSG frequency variations. d) DC link voltages for each power interface.

- If the load-side converters are interconnected on the ac side to supply an islanded load, or to cogenerate with existing distributed generation, frequency and voltage droop control schemes have to be applied for appropriate active and reactive power.
sharing, respectively. Performance of frequency droop control was demonstrated through simulations.

- Grid-connected operation was also presented using simulations, where the maximum available power from each kinetic turbine in the Farm is transmitted to the grid, similar to grid-connected wind farms.
Chapter 7

Conclusion and Proposed Future Work

This thesis explains the advantages of river kinetic hydropower as a viable clean renewable resource. Kinetic turbines are relatively inexpensive, as they do not require dams or powerhouses. They involve one or more submerged turbine-generator units installed on a river at locations with relatively high-velocity currents.

Compared to wind, kinetic hydro is expected to produce reliable and continuous electrical power throughout the year, as water flows steadier than wind and its variations tend to be predictable.

The main contributions of this thesis are summarized in the following section. A few potential topics for further research in this area are also proposed.

7.1.1 Original Contributions

1- **Comparative Analysis of Feasible Power Interface Configurations:** Several electronic power interfacing techniques were introduced and compared for different types of alternative-energy generation. From this analysis, options suitable for hydrokinetic applications could be selected.

2- **Design and Construction of a Hydrokinetic Power Delivery System:** In order to investigate the technical aspects of hydrokinetic technology and with a view to future commercialization of this application, a new research kinetic turbine platform was designed and implemented. The platform comprises a
shrouded horizontal-axis turbine capable of producing up to 40 kW at a water velocity of 3 m/s. The turbine drives a permanent-magnet synchronous generator (PMSG) rated at 60 kVA with a nominal frequency of 276 Hz. The high nominal frequency allows for a compact and light generator.

An electronic power interface had to be implemented to match the high-frequency (and often variable) PMSG output to a 60 Hz ac system. The power interface is capable of supplying an islanded load or transferring power to the grid. A few feasible topologies were considered in the design stage. Due to its advantages, back-to-back VSC-based scheme was selected for the implemented platform. A long cable connects the PMSG (in the water) to the power interface (on the shore).

The proposed design needs special considerations, which are different from those in conventional wind-power applications. A summary of those requirements are listed below.

- In most wind generators that use a full back-to-back converter arrangement, the converter is located in the nacelle, in close proximity to the generator. This is difficult for an underwater turbine. The VSC converter and PMSG in the implemented platform are linked via a 120-m long cable. PWM switching pulses on the VSC side trigger travelling wave reflections on the cable, thus producing steep voltage wave-fronts and voltage multiplication at the PMSG terminals. This could lead to insulation failures. Hence, a filter had to be considered for the PMSG-side converter to shelter the PMSG from such over-voltages. The filter also has to accommodate the wide range of PMSG frequency variations (200 Hz to 500 Hz).
Shaft-encoder-based speed measurements commonly used in full-converter wind turbines with PMSG was not possible due to mechanical and electrical integrity issues. An encoder could not be installed on the underwater sealed generator unit. It was also impossible to reliably transfer the signal to the PMSG-side converter located 120 m away on the shore. Hence, an alternative approach was applied in the PMSG-side controls. A phase-locked loop (PLL) with a wide tracking range was used as a substitute for a shaft position sensor.

The thesis shows that the steady state and dynamic performances, including aspects such as the PLL tracking, converter response to load changes, generator-side filter performance, etc., are acceptable. It should be noted that the generator used in this system operates over a wide frequency range (200 Hz to 500 Hz). This wide range does not occur in wind and micro-hydro generation applications (which have gate structures) and hence it is necessary to confirm that converters can be designed for such extreme variation.

3- Modelling and Simulation for Design: Electromagnetic-transients-type (emt-type) simulation was used in the design phase to confirm the ratings of the components selected for the converters (such as low-pass filters, etc.). The designed strategies to control the power interface in each of the two operation modes were also validated through emt-type simulations. The turbine-generator, the converter’s power electronic devices, the transmission system and the load/grid were modeled in detail in order to achieve credible results.
4- **Full-load Pre-commissioning Tests:** The power interface system was constructed based on the conclusions obtained in the design stage. Pre-commissioning tests were performed in laboratory by emulating the turbine using a variable-speed prime mover. The PMSG used in the actual platform was used in those tests. The load-side converter was connected to the grid at its nominal voltage and frequency. The system was tested up to its rated power. Acceptable performance of the power interface was confirmed in those tests. The results provided a high level of confidence for final tests in the field.

5- **Field Installation:** In 2011, the developed kinetic turbine and power interface were installed in the field at Pointe du Bois in Manitoba in Canada. The power interface was integrated into the grid at 600 V, 60 Hz. However, Severe lack of precipitation resulted in low water flow (<1 m/s) at the site. This was much lower than the turbine’s design minimum water speed of 2 m/s. The turbine could only be loaded up to less than 10% of its rating.

6- **Investigation of Turbine Control Strategies:** A few strategies were introduced and investigated for turbine control in grid-connected mode. When integrated into the grid, it is often desirable to transfer as much power as possible from an alternative energy source to the grid. In a kinetic hydro plant, installation of transducers to measure flow velocity and turbine speed make the turbine design more complicated. Sensors are prone to damage caused by debris, floating ice, etc. Accessibility for repair can be an issue in a kinetic hydro plant, as the turbine generator are submerged and anchored in the current. Also, transmission of signals from the sensors (in the water) to the control
system (on the shore) may not be straightforward. Hence, sensorless control techniques seem to be advantageous in this application.

- The turbine control strategies investigated in this thesis include perturb-and-observe (P&O) maximum power-point tracking (MPPT) and a method based on the turbine characteristics \( (k\omega^3) \). The performances of those techniques were investigated through simulation.

7- Development of Topologies and Control Methods for Kinetic Farms: Flow in a river tends to be steadier than wind, and its variations seem to be more predictable. Hence, application of several kinetic turbines in a river seems to be a viable option where flow levels are sufficient. This can allow for establishing kinetic farms, analogous to wind farms. Several feasible configurations for kinetic farms were introduced. The back-to-back VSC-based power interface was used in all of the investigated schemes.

- Power sharing among the kinetic turbines in a kinetic farm needs to be regulated, particularly when the Farm energizes an island, or cogenerates with other distributed generation sources to supply a micro-grid. Flow variations change the power available at each turbine. Therefore, the turbine exposed to higher flows should take over a larger portion of the load demand. Methods for automated power sharing among the turbines were proposed for two main power interface interconnection schemes: interconnection at the VSCs’ dc links, and interconnection at the ac side.

- It was shown how effective load shedding could ensure stable operation of a kinetic turbine unit integrated into a kinetic farm.
7.1.2 Proposed Future Work

The following aspects of hydrokinetic applications seem to be potential topics for further research in this area:

- Application of other types of generators (such as induction machines) and electronic power interface configurations can be studied. Either full-converter or doubly-fed induction generator (DFIG) scheme may be viable options.

- Different converter topologies can also be investigated for synchronous or permanent-magnet generators, such as diode rectifier + dc-dc converter + dc-ac converter. A comparison between those options and the back-to-back VSC-based scheme will be valuable.

- Insufficient flow during field tests did not allow for gathering meaningful information regarding the impact of mechanical disturbances such as turbulence, temporary flow fluctuations, etc. Inclusion of those details in the turbine model can help investigate the effects of such disturbances on the performance of the power interface. Appropriate control strategies may need to be developed to mitigate those disturbances.

- Cogeneration with other distributed-generation sources such as diesel-generators, etc. or inclusion of energy storage in a hydrokinetic plant seem to be feasible solutions. Battery storage can supplement the kinetic turbine during peak load or when flow is insufficient. Under low load conditions, the power from the turbine can charge batteries.

Finally, if test conditions permit, observing the performance of the developed hydrokinetic platform over long-term operation can provide helpful data on the
feasibility and cost-effectiveness of this technology. This seems particularly interesting when comparing kinetic hydro with conventional fossil-fuel solutions in remote areas.
References


[37] Manitoba Hydro Interconnection Guideline for Connecting Distributed Resources to the Manitoba Hydro Distribution System (DRG2003), Revision 0, January 2003.


Appendix A. Vector-Control Strategy in Grid-connected VSC Schemes

The power control concept explained in the previous section can be implemented using the vector-control scheme. In this section, the current-regulated vector-control strategy is explained. The magnitude and phase angle of the converter ac voltage \((V_i)\) are adjusted to control its ac current \((I)\) such that the desired active and reactive power levels are achieved \([48]\).

The single-line diagram in Figure A-1 shows a 3-phase ac system (denoted by ‘ac bus’) linked to a dc system through a VSC. The dc system is represented by a variable dc current source \(I_{\text{load}}\).

At the ac side of the system, the Kirchhoff’s voltage law (KVL) can be written as:

\[
\begin{bmatrix}
  v_a \\
  v_b \\
  v_c \\
\end{bmatrix} = R \begin{bmatrix}
  i_a \\
  i_b \\
  i_c \\
\end{bmatrix} + L \begin{bmatrix}
  \frac{d}{dt} i_a \\
  \frac{d}{dt} i_b \\
  \frac{d}{dt} i_c \\
\end{bmatrix} + \begin{bmatrix}
  v_{1a} \\
  v_{1b} \\
  v_{1c} \\
\end{bmatrix}
\]

\((A-1)\)

The variables and parameters in \((A-1)\) are introduced below:

- \(R\) and \(L\): The resistance and inductance of the ac-side impedance;
- \(v_a, v_b\) and \(v_c\): The ac bus phase voltages;
\(v_{la}, v_{lb}\) and \(v_{lc}\): Phase voltages at the VSC’s ac terminals;

\(i_a, i_b\) and \(i_c\): AC line currents.

To simplify the analysis, the 3-phase ac voltage and current quantities are mapped onto the rotating \(dq0\) reference frame using the Park transformation [21] given in (A-2). The inverse Park transformation is given in (A-3).

\[
T = \frac{2}{3} \begin{bmatrix}
\cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{4\pi}{3}) \\
-\sin \theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\Rightarrow \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = T \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}
\tag{A-2}
\]

\[
T^{-1} = \begin{bmatrix}
\cos \theta & -\sin \theta & 1 \\
\cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\
\cos(\theta - \frac{4\pi}{3}) & -\sin(\theta - \frac{4\pi}{3}) & 1
\end{bmatrix}
\Rightarrow \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = T^{-1} \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix}
\tag{A-3}
\]

The same transformation can be applied to the phase currents to obtain their respective \(dq0\) components. Using (A-2) and (A-3), equation (A-1) can be rewritten as:

\[
T \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = T \times R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + T \times L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + T \begin{bmatrix} v_{1a} \\ v_{1b} \\ v_{1c} \end{bmatrix}
\Rightarrow
\]

\[
\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + T \times L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + \begin{bmatrix} v_{1d} \\ v_{1q} \\ v_{10} \end{bmatrix}
\Rightarrow
\]

\[
\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \begin{bmatrix} R & -\omega L & 0 \\ \omega L & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} + \begin{bmatrix} v_{1d} \\ v_{1q} \\ v_{10} \end{bmatrix}
\tag{A-4}
\]
In (A-4), \( \omega \) is the angular frequency of the ac voltage. For a balanced 3-phase system, the zero-axis voltages \( v_0 \) and \( v_{10} \) as well as the zero-axis current \( i_0 \) are zero.

If the \( d \) axis of the rotating \( d-q \) reference frame is aligned with the phase-a voltage \(- (v_a)\), then:

\[
\begin{align*}
    v_d &= V_m \\
    v_q &= 0
\end{align*}
\]  

(A-5)

In (A-5), \( V_m \) is the peak of the phase voltage \( v_a \). One method to achieve such an alignment is through a phase-locked loop (PLL) ([32][33]). Phase-locked loop was explained in section 3.4.3. Assuming a balanced 3-phase system and using (A-5), (A-4) can be simplified as:

\[
\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} R & \omega \\ -\omega & -R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{v_d - v_{1d}}{L} \\ -\frac{v_{1q}}{L} \end{bmatrix}
\]  

(A-6)

The objective of this control method is to regulate \( i_d \) and \( i_q \) by controlling \( v_{1d} \) and \( v_{1q} \), respectively. This will help establish the desired power transfer level. Controlled voltage references \( v_{1d} \) and \( v_{1q} \) can be selected as shown in (A-7):

\[
\begin{align*}
    v_{1d}^* &= v_d - x_1 \\
    v_{1q}^* &= -x_2 \quad \text{(since } v_q = 0) \\
\end{align*}
\]  

(A-7)

Here, the asterisks denote reference values. In (A-7), \( x_1 \) and \( x_2 \) are auxiliary variables. They can be outputs of two PI controllers to regulate \( i_d \) and \( i_q \) currents respectively, as shown in Figure A-2. In this figure, \( i_d^* \) and \( i_q^* \) are the reference
values for $i_d$ and $i_q$, respectively. The reference angle $\theta$ is obtained

![Diagram of vector control of d-q currents]

Figure A-2: Vector control of $d$-$q$ currents

using a PLL locked onto the phase voltage $v_a$. The VSC will produce the set of 3-phase voltages $v_{1abc}^*$, output by the vector controller.

In (A-7), $v_d$ and $v_q$ (=0) are used as feed-forward components, which in turn improve the response of the current controllers. Using (A-7), equation (A-6) can be rewritten as:

\[ V_{1a^*} = V_m \sin(\theta + \pi/2) \]
\[ V_{1b^*} = V_m \sin(\theta + \pi - 120) \]
\[ V_{1c^*} = V_m \sin(\theta + \pi + 120) \]

where $V_m$ is the magnitude of the reference voltage and $\theta$ is the reference angle.
\[
\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{x_1}{L} \\ \frac{x_2}{L} \end{bmatrix}
\]  
(A-8)

Equation (A-8), however, implies that still a change in either of \( v_{ld}^* \) and/or \( v_{lq}^* \) will affect both \( i_d \) and \( i_q \) due to the ‘coupling’ between the two equations. This may have a negative impact on the dynamic response of the current control scheme. The equations can be decoupled using compensation terms ([37] and [48]). Equation (A-6) can be rearranged as below:

\[
\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{\begin{bmatrix} v_d - v_{ld} + \omega L \cdot i_q \\ -v_{lq} - \omega L \cdot i_d \end{bmatrix}}{L}
\]  
(A-9)

\[
\begin{cases}
  v_{ld}^* = v_d - x_1 + \omega L \\
  v_{lq}^* = -x_2 - \omega L
\end{cases}
\]  
(A-10)

Substituting for the voltage references from (A-10), (A-8) is transformed into the following set of equations:

\[
\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{x_1}{L} \\ \frac{x_2}{L} \end{bmatrix}
\]  
(A-11)

In other words, \( i_d \) and \( i_q \) are controlled by \( x_1 \) and \( x_2 \), respectively, with no influence from the other axis’s current. This control scheme is referred to as decoupled vector control and is illustrated in Figure A-3.
A comparison between the decoupled and non-decoupled schemes is demonstrated below through an example.

**Example: Comparison between non-decoupled and decoupled vector control**

The schematic diagram of a grid-connected VSC is shown in Figure A-4.

The converter is connected to a 600V, 60 Hz ac system. In this example, it is assumed that the VSC is supplied by a dc voltage source with a nominal voltage of $V_{dc} = 985$ V and operates at a switching frequency of $f_{sw} = 6$ kHz. The low-pass filter outlined in the figure attenuates the PWM switching disturbances. The per-phase
circuit of the filter and the Bode diagram of the filter transfer voltage \( H(j\omega) = V_{out}(j\omega)/V_{in}(j\omega) \) are depicted in Figure A-5.

![Filter Circuit and Bode Diagram](image)

Figure A-5: a) Per-phase diagram of the filter. b) Bode diagram of the transfer voltage.

The cut-off frequency of the filter is 1.51 kHz. It can be observed in Figure A-5-b that the filter attenuates the PWM switching harmonics in the output voltage by -30.8 dB (or 0.02884), while passing the fundamental frequency components without change. The VSC responses to step changes in \( i_d^* \) and \( i_q^* \) are demonstrated.
in Figure A-6 and Figure A-7 with non-decoupled and decoupled vector control, respectively. In both simulations, the set-point $i_q^*$ is changed from zero to -100A and then +100 A (i.e. -100 A and +200 A steps). This is followed by steps in $i_d^*$ from zero to +100 A and then to -100 A (i.e. +100 A and -200 A steps).

Responses of the non-decoupled vector control scheme are plotted in Figure A-6. It can be observed that a change in $i_d^*$ (or $i_q^*$) causes a disturbance in $i_q$ (or $i_d$).

Those transient disturbances are eliminated using decoupled vector control, as shown in Figure A-7. This figure clearly demonstrates improved dynamic performance of the VSC when decoupling is included in the current controllers.
Figure A-7: Responses of the VSC currents with decoupled vector control to $i_q^*$ and $i_d^*$ steps.

a) -100A and +200A steps applied to $i_q^*$. b) +100A and -200A steps applied to $i_d^*$.

The current set-points $i_d^*$ and $i_q^*$ are normally the outputs of two external regulators. The $d$-axis current reference $i_d^*$ is normally adjusted for regulating the VSC’s active power level or its dc link voltage. The $q$-axis set-point $i_q^*$ is used for controlling either the VSC reactive power or the ac voltage magnitude at the point of interconnection to the grid.