UNIVERSITY of RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY

ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

UNIVERSITY OF RWANDA

College of Science and Technology

OPTIMIZATION OF THE POWER CONVERTER FOR INDUCTION MACHINE ROTOR IN HYDROPOWER APPLICATIONS.

BY

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A dissertation submitted in partial fulfillment of the requirement for the Degree of MASTER OF SCIENCE IN RENEWABLE ENERGY in the African Center of Excellence in Energy for Sustainable Development (ACE-ESD) at University of Rwanda.

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Kigali, November 2021

DECLARATION

I declare that this Dissertation titled *"OPTIMIZATION OF THE POWER CONVERTER FOR INDUCTION MACHINE ROTOR"* is my original research project except where acknowledged, and it has been passed through the anti-plagiarism system and found to be compliant and this is the approved final version of the project.

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Signed, 19./11/2021

DEDICATION

To Almighty God,

To my spouse, Jeannine NZOSABA, without her endless love and encouragement I would never have been able to complete my graduate studies,

To my son, IRIHO Ellis Davina,

To my daughter, IRUMVA Mia Dara,

To my parents,

To my brothers and sisters,

To my aunts and uncles,

To my cousins, nephews and nieces,

To my regretted:

- *little brother, MUJENAMA, gone so soon,*
- *cousin, KANEZA, gone so soon,*
- *grand-father, KINUNDA,*

All of them (together), are victims of the murderous tragedy of 1993 which bereaved our country.

To the Circle of SAVE's Descendants, "CDS-UMUNYAKARAMA";

To the great family of the "Forum pour la Mémoire Vigilante", FMV in the acronym, for its encouragement in my studies and its hard work towards the most deprived people, in particular refugees, internally displaced persons, immigrants as well as returnees;

To my friends and classmates;

This research project is dedicated.

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At the end of our work, it is our honor to express our sincere acknowledgements to those who, from near or far, have contributed to the accomplishment of the latter because it is the sacrifices fruit of more than one.

Above all, we want to give glory to God who guided us throughout our student life, who taught us from our youth and who gave us the chance to reach this stage.

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We cannot end without thanking all of our classmates. You have been able to create and enhance, through our understanding and cooperation, a favorable climate for our training. Thank you so much.

May God bless you All.

ABSTRACT

The aim of this research project, dissertation, is focused on the optimization of the power converter for induction machine rotor in hydropower applications. In fact, a micro-hydroelectric power station, a low-power hydroelectric power generation installation, uses for most of the cases an induction generator to transform mechanical energy from hydraulic turbine into electric energies. The electrical energy produced is transmitted into network or load island by using the direct-connection method. The last one has serious limitations on all production and transmission energy system such as quality of power is deteriorated close to the induction machine, limiting possible conditions of power transmitted control and problems related to the highest of starting currents. After a critical analysis and reviewing the previous methods with their weakness, in this research project, an AC-DC-AC power converter is presented as solution to be connected with the induction generator before injecting power into the grid-side or island part. The main objectives of this work were achieved and the simulation of results are conducted with MATLAB/Simulink software, with also some specific experimental set-up to achieve our expected outcomes. The major results of our project were shown in Fig.4.1, Fig.4.2, Fig.4.3, Fig.4.4, Fig.4.5 and Fig.4.6. Our recommendations were formulated and a general conclusion of our research project was carried out.

Keys words: Power Converter, Induction Machine Rotor, Hydropower Plants.

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LIST OF ACRONYMS / ABREVIATIONS

- A : Ampere ;
- AC : Alternating current ;
- $\cos\varphi$: Power factor.
- DC **:** direct-current ;
- f : frequency ;
- F_{mr}: Magnetomotive force at the rotor;
- F_{ms}: Magnetomotive force at the stator;
- Hz : Hertz ;
- I_L: Current line;
- I_m: Magnetizing current;
- I_{mr}: rotor currents (that create magnetomotive forces at the rotor);
- I_{ms}: stator currents (that create magnetomotive forces at the stator);
- I_p : Current in the phase ;
- i_G : generator current;
- KW : kilowatts ;
- m: Transformation ratio;
- mH : Milli-henry ;
- µF : Microfarads;
- N_s: Synchronous speed;
- P : Number of pole ;
- P_m : Mechanical power ;
- P_{ab} : Power absorbed ;
- P_{act} : Active power ;
- P_{elm}: Electromagnetic power;
- P_{react} : Reactive power ;
- rpm : revolution per minute ;
- s : Slip ;
- S_{app}: Apparent power of the asynchronous generator;
- T_{elm} : Electromagnetic torque;
- THD : Total harmonic distortion;
- T_m : Mechanical torque at the output of the asynchronous generator ;
- T_u : Useful torque ;

- u_G: generator voltage.
- U_l: Line voltage;
- U_p : Voltage in the phase ;
- V : Volts ;
- ω_e : Electrical pulsation;
- Ω_r : Angular velocity of the rotor;
- η_m : Efficiency of the machine.
- η_{gen}: Asynchronous generator efficiency;
- δ: Electric angle of current at the rotor;

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CHAPTER 1. INTRODUCTION

1.1. Background

Satisfying the desire of the majority of the people in the world and the need for energy conservation from the environmental side has made the renewable energy system as mandatory among other energy systems. Hydraulic power is the first renewable energy for the production of electricity. In 2004, 154 countries recognized hydropower as a renewable energy source. Because it consists of water from annual precipitation over a large area, the source of hydropower is inexhaustible. At the exit of the pipe, in the power station, the force of the water turns a turbine which in turn operates an alternator / generator. Because of the energy supplied by the turbine, the alternator / generator produces an alternating electric current. The power of the plant depends on the height of the fall and the flow of the water [1].

Therefore, our topic of the project is related to hydropower applications, specifically small hydropower plants or micro hydropower plants which are power plant that use hydraulic energy to generate electricity on a small scale. This electrical power is produced by the generator which is an alternator or a rotating machine that converts the mechanical energy supplied by the turbine into alternating current electrical energy. There are two types of generators in small hydroelectric power stations which are alternators (synchronous machines) for all power plants not charging on the network and asynchronous generators for those which flow on a powerful network. Pico-hydropower plants (10 to 100 kW) are sometimes equipped with a direct current machine or an asynchronous machine self-excited by capacitors. In this case, the quantity of capacitors and the load ensure voltage and frequency regulation [2].

The asynchronous machine is, by design, easier to maintain than the synchronous machine, which often has rings and brushes for small powers. However, it can only be used in the case of a flow on a network capable of imposing the frequency and providing the reactive power necessary for its magnetization. That’s why, this induction generator is very suitable for small hydroelectric generations. The asynchronous machine has a stator similar to that of conventional three-phase machines, most often made up of stacked magnetic sheets provided with notches in which the coils are inserted. In addition, A doubly fed induction generator works by mechanically turning the rotors faster than in the case of synchronism. Its excitation system is generally supplied by the electrical network. It should be noted that for this reason, asynchronous machines are unable to restart a de-energized distribution system. More commonly, phase correction capacitors allow self-excitation [3].

With a machine operating under load both magnetic fields are opening up a torque depending angle in between, but under static load the both revolutions per minute must be the same, otherwise no constant torque can be transmitted. Then, by introducing varying speeds solution, speeds rotation of magnetic field must be decoupled from its conventional generator origin: either on the stator side with decoupled stators of network frequency, on other side the rotor element is considered. This premium solution requires a frequency of conversion system of windings stator with Grid. This second solution requires a magnetic field revolving around the rotor element, produced by three-phase rotor windings supplied via frequency converters connected to the rotors [4], [5].

Thus, it is necessary to think about how to minimize the interruption in power supply when the doubly fed induction generator is directly connected to the network or to the isolated load, about limitation of the highest currents at the start-up step when we have direct connection method between the generator and the grid / island, the possibility of contributing on improving the conditions of transmission of the power.

1.2. Problem statement

Renewable energy production systems are widely explored due to a major interest linked to sustainable development. The advantages of hydroelectricity are its renewable nature, its low operating cost and its low greenhouse gas emissions; the storage capacity of its reservoirs helps offset variations in demand as well as those of intermittent energies (wind, solar).

Then, in small hydropower plants, which possess an asynchronous generator, in direct-connection between generator and grid side or load island side, the main problem is described by the following serious issues which could be inevitably: quality of power is deteriorated close to the induction machine, limiting possible conditions of power transmitted control and problems related to the highest of starting currents. All this leads to the major problem of power losses and progressive / considerable decreasing efficiency of the system.

1.3. Aim of the project

The aim of this research project is focused on optimization of the power converter for induction machine rotor in hydropower applications.

1.4. Objectives

i) Show the need of using the doubly fed induction generators and their control systems in small hydroelectric generations;

ii) Complete the choice and specific discussion of a suitable power electronic converter for induction generators in small hydropower applications;

iii) Use of specific power electronic converter to minimize the very highest start-up currents and enhance power transmitted control;

iv) Complete the results analysis by simulations process and practical experimental set-up;

1.5. Scope of the work

This section of our research project contains the areas to be covered by the present work. Each research work must be defined in a well-determined field to prevent the researcher from working in a vague and unlimited universe.

Given the extent of technical, environmental, economic, financial studies, etc, which could be carried out in parallel for a such project, our main work focuses much more on the technical aspect. Then, our project is about doubly fed induction generator used in small hydropower plants and their control. Specifically, it is limited to the use of suitable power electronic converter in the connection between induction machine rotor and network side or island part, in order to optimize the energy production system in hydroelectric applications.

1.6. Expected outcomes and significance of the study

1.6.1. Expected outcomes of the study

After this research project, we are expecting to come up with method which if used will make the followings:

i) The complete choice with particular discussion of the suitable proposed method will be carried out in this research project;

ii) The highest start-up currents in connection between induction generator and network side or island part, will be minimized;

iii) The power transmitted control systems will be enhanced;

iv) The optimization of the power converter for induction machine rotor in hydropower plant applications, will be performed.

1.6.2. Significance of the study

Our study is important because it makes a clear contribution in the field of hydroelectric production. By now, hydropower remains the largest source of renewable electricity generation in the world. It represents 16.6% of global electricity production, a percentage much higher than all other renewable energies combined, and will play an important role in the energy transition. Therefore, people will learn from our project especially how is the importance of application of power electronic converters in connection between induction generator and network side or island side, in small hydropower plants.

1.7. Conceptual framework

The development of large hydropower plants has become increasingly difficult in many industrialized countries due to the shortage of development sites and environmental restrictions. However, there are still many suitable sites for the development of small hydropower plants or "small scale" which denotes a power range from a few kilowatts to a few megawatts (generally <10MW).

This potential gives an important place to small hydropower plants in the future energy mix with targeted applications such as supplying isolated sites, supporting the local or interconnected grid. Variable speed hydroelectricity is little explored, especially in generation.

Thus, the main idea of the work carried out in this thesis project is to use the possibilities offered by electronic power converters to optimize the control of power losses in small hydropower generations which are using an induction machine rotor. The use of power electronic converters in renewable energy integration, especially in hydropower applications, are very important to achieve good efficiency.

CHAPTER 2. DOUBLY FED INDUCTION GENERATOR AND THEIR CONTROL SYSTEMS IN SMALL HYDROPOWER APPLICATIONS

2.1. Introduction

The global energy crisis makes appear in every country of the needs, sometimes vital, for energy sources replacing thermal power stations and generators groups becoming too expensive. In addition, the concern to preserve the natural resources directing developments towards energies ceaselessly renewable. This gave back to harnessing the energy of waterfalls a new interest.

In addition to large power plants intended to supply national grids which transport large powers, micro-plants make it possible to produce energy in small powers at a competitive price. Hydroelectricity is a renewable energy source based on the natural water cycle. It is considered to be the most mature, reliable and cost-effective renewable energy generation technology available [6].

There are two principal AC machines used to generate electrical power: synchronous machines and asynchronous machines. The asynchronous generator generally equips a mini-power plant or micro-hydraulic power plant. The asynchronous machine is an alternating current machine which does not have a connection between the stator and the rotor. The term asynchronous comes from the fact that the speed of the rotor is different from the pulsation of the stator currents.

Any electrical machine in which the rotational speed of the rotor is equal to the rotational speed of the rotating field is called a synchronous machine. In order to achieve such operation, the rotor magnetic field must be generated either by magnets or by an excitation circuit. That said, that in permanent mode the position of the rotor magnetic field is then fixed with respect to the rotor, this imposes an identical speed of rotation between the rotor and the rotating stator field [7], [8].

However, for the case which concerns us, these asynchronous machines do not have an excitation circuit like the alternators. It is nevertheless necessary to provide the power of magnetization as well in generator as in motor; it is not a usable power, called active power, but a fictitious power, reactive power, corresponding to a component of the current with zero power factor [9].

This current can be borrowed from the network but can also be obtained statically by connecting a capacitor bank in parallel to the machine. In addition, by adjusting these capacitors precisely, it is possible, under certain conditions, to use an asynchronous generator outside a network, autonomous operation to supply an isolated load. Induction machines, generally useful when there is impossibility of controlling motive power, especially for winds power systems and hydraulic operation.

In this case, the rotor does not operate in synchronism with the system voltages. At the output, for an induction machine, the frequency equals for most of the time around two percent (2%) and three percent (3%) below frequency determined based on the following expression $F = \frac{N \times P}{120}$ where N expressed in rpm (revolutions per minute) is nominal rotor speed, F is the frequency (Hz) and P is the number of poles formed by the stator windings. If the speed is kept constant, the frequency varies according to the power level [10].

2.2. Electromechanical generators

An electromechanical generator converts the mechanical energy it receives at its shaft (turbine) into electrical energy distributed to the consumer. It is about active energy. Normally, the consumer can be:

- The interconnected network which fixes the voltage and the frequency;
- An isolated network to which the producer must guarantee a voltage as well as a frequency which must both be fixed and stable within an acceptable range for the consumer's devices.

In small-scale electrical energy production installations, a choice should be made between two types of generators:

- the synchronous generator;
- the asynchronous generator.

In both cases:

- the machine is composed of a rotor and a stator;
- the stator winding, generally three-phase, is the site of an induced voltage at the terminals of each phase.

2.2.1. Synchronous generator

- **Generalities**

In motor operation, the frequency of rotation of the machine is strictly imposed by the frequency of the alternating current which supplies the stator. In the same way in generator, the electric frequency will be imposed by the speed of rotation. This property justifies the designation of synchronous.

The frequency f delivered by the synchronous generator is directly proportional to the speed of rotation n of its rotor (Table (2.1)) : $f = p \times n$, where p, the number of pole pairs, is the proportionality factor.

Table (2. 1) : Some values of nominal speed for 50 Hz

Number of poles (2p)	Speed N (rpm)
2	3000
4	1500
6	1000
8	750
10	600
12	500

- **Principle**

In a synchronous machine (Figure 2.1), we distinguish:

- the inductor (rotor) through which a direct current flow or sometimes consists of permanent magnets;
- the armature (stator) traversed by alternating currents, generally three-phase.

The three-phase stator is composed of three groups of conductors, housed in the notches of the stator. These are combined to form three identical windings (one per phase) and offset by an electrical angle of 120 ° to each other. They are traversed by three currents which form a three-phase system and create an exciting rotating field.

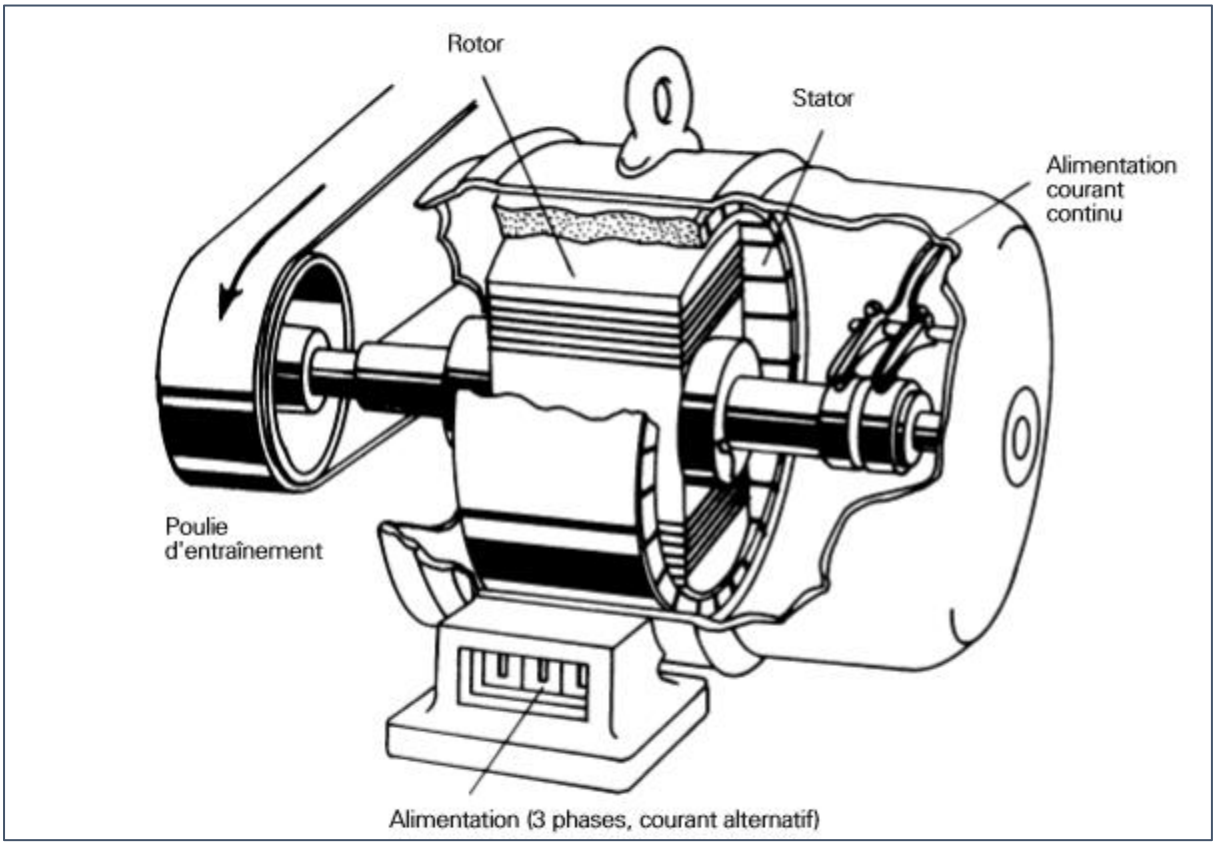


Figure (2. 1) : Schematic representation of a synchronous machine

The conductors create a rotating field with sinusoidal distribution, comprising 2p poles, whose speed Ω_{rot} is linked to the electrical pulsation ω_e of the supply currents and to the number p of pairs of poles determined by the stator winding.

$\Omega_{rot} = \omega_e \times p = 2 \times \pi \times n_s$ …………………………….. (2.2)

- Ω_{rot}: Speed in rad/sec;
- n_s: Speed in rpm;

The role of the rotor is to create the rotating magnetic field necessary to generate the induced alternating voltage at the terminals of the stator.

The rotor, from a magnetic point of view, is therefore a magnet which can be of 2 types:

- the rotor with permanent magnets, in which the flow created is constant. The induced voltage therefore depends only on the frequency.
- the rotor with excitation winding, in which the flux varies with the direct current injected into the coil (excitation current).

From a constructive standpoint, the following considerations should be noted:

- the rotor with smooth poles where the air gap is constant;
- the rotor with salient poles.

For economic reasons, small power salient pole machines are rare. Manufacturers instead use sheets of asynchronous machines rotors. The winding is mounted in the notches so as to have the desired number of poles.

- **Power balance - efficiency**

The power absorbed (P_{ab}) by the synchronous generator is the mechanical power (P_m) to the machine shaft. $P_{ab} = P_m$.

The active power P_{act} supplied to the network, or to consumers, is expressed as a function of the voltage at the terminals of a phase and the current in each phase by:

$P_{act} = 3 \times U_p \times I_p \times \cos\varphi$ ………………………….. (2.4)

And depending on the phase-to-phase voltage and the line current:

$P_{act} = \sqrt{3} \times U_l \times I_l \times \cos\varphi$ ……………………….. (2.5)

The difference between the powers absorbed and supplied represents the losses in the synchronous generator (this is shown schematically by Figure (2.2) below):

$P_{ab} - P_{act} = \sum LOSSES$ …………………………… (2.6)

The different losses are:

- losses by friction and ventilation;
- losses in the magnetic circuit of the stator, or iron losses;
- copper losses due to the passage of current in the 3 stator windings;
- losses due to the Joule effect in the excitation winding.

The efficiency is the ratio between the power supplied and absorbed:

$\eta = \frac{P_{act}}{P_{ab}} = \frac{P_{act}}{P_{act} + \sum Losses}$ …………………… (2.7)

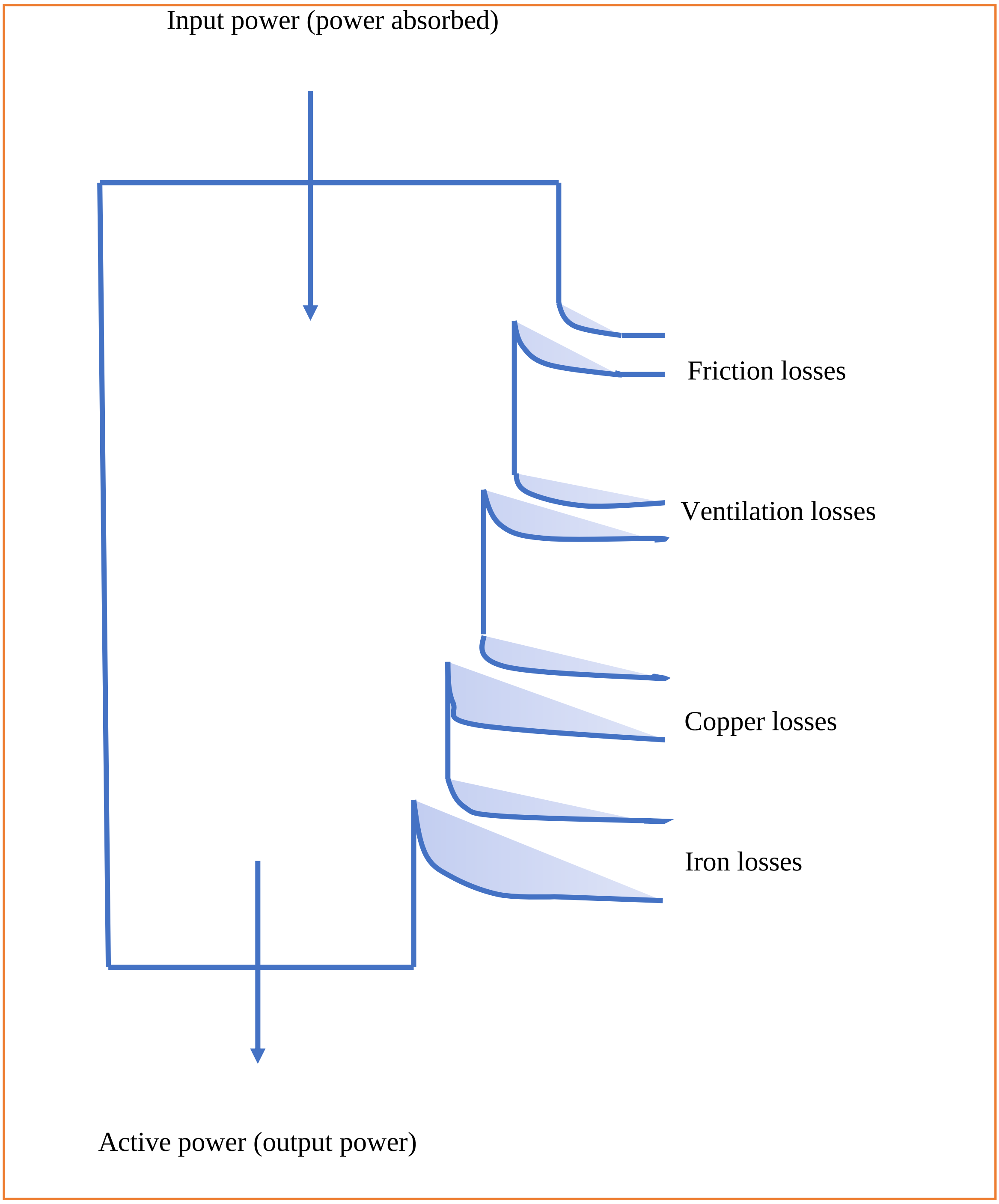


Figure (2. 2) : Power balance on synchronous generator

2.2.2. Asynchronous generator

- **Generalities**

The asynchronous machine, also called induction machine, can, like all electrical machines, operate as both a generator and a motor. However, it is the most widely used electric motor, because it is simple, robust in construction, and relatively inexpensive. These advantages are mainly due to the fact that the rotor is not connected to any external voltage source, except for special use with a wound rotor.

It owes its name of induction machine to the fact that the rotating field of the stator induces alternating currents in the rotor circuit [11].

- **Principle**

The asynchronous machine consists of a fixed circular element called a stator, in which a cylindrical movable element called a rotor rotates (Figure 2.3). The two elements are made of stacked magnetic sheets, of low thickness (0.2 mm, 0.5 mm), in order to reduce iron losses due to the presence of alternating magnetic fields [11].

- The stator of an asynchronous machine is identical to the stator of a synchronous machine.
- The rotor has a short-circuited winding. It can also consist of a solid cylinder of conductive material. In both cases, the rotor winding forms a closed circuit on itself.

The squirrel cage rotor is the most commonly used. It consists of copper or aluminum bars placed in notches and connected to each other at each end by a ring of the same material. As the induced voltages are generally low, the bars are often not isolated from the rotor body (sheets).

The wound rotor consists of coils of insulated wire placed in notches and connected, like the stator winding, so as to produce a three-phase winding. In normal operation, the three phases are short-circuited together. Under the action of the rotating field, voltages are induced in the rotor conductors. The latter are then traversed by induced currents (eddy currents) which create the induced rotating field.

The interaction of the excitatory field and the induced field creates a mechanical torque responsible for the rotation of the machine.

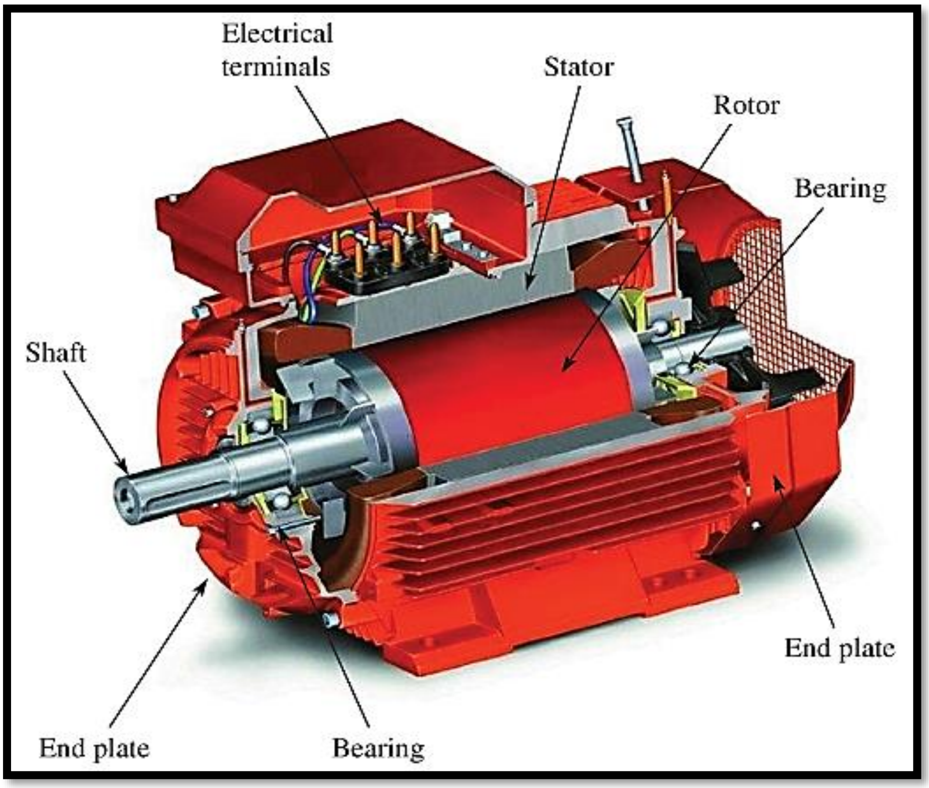


Figure (2. 3) : Constitution of an asynchronous cross-sectional generator [11]

- **Powers and torque**

The active power (P) absorbed by a motor or supplied by a generator can be expressed by:

$P = \sqrt{3} \times U \times I \times \cos\varphi$ ……………………………… (2.7)

Where:

- U: Voltage between network phases;
- I: Line current;
- φ: Phase-shift between phase voltage and current.

The useful mechanical power P_m at the shaft of a motor is a function of the useful torque T_u and the angular speed Ω_r of the rotor.

$P_m = T_u \times \Omega_r$ …………………………………… (2.8)

Where: $\Omega_r = 2 \times \pi \times n$

The ratio between the absorbed power and the useful power gives the efficiency η_m of the machine:

$\eta_m = \frac{P_{act}}{P_{abs}}$ ……………………………………….. (2.9)

The difference of these two powers constitutes the sum of the losses dissipated in the machine:

$P_{abs} - P_m = \sum Losses$ …………………………. (2.10)

These losses are of four types:

- Mechanical: P_{fr+ve} due to friction and ventilation;
- Iron: P_{iron} by hysteresis and eddy currents due to alternating magnetic fields. At the rotor, they are negligible due to the low frequency of the field.
- By Joule effect:
    - to the stator:
      $P_{Cop,s} = 3 \times R_{st} \times I_{st}^2$ ……………………….. (2.11)
      Where, R_{st} is the stator resistance.
    - to the rotor:
      $P_{cop,r} = Z_{rt} \times R_{rt} \times I_{rt}^2$ ………………………. (2.12)
      where R_{rt} is the resistance of a rotor bar; Z_{rt} is the number of rotor bars.
- Additional: P_{add} due to higher harmonics of the magnetic field and the presence of notches; they are estimated at around 0.5% of the useful power.

The energy balance, or power flow, allows a detailed analysis of the conversion of mechanical energy into electrical energy (Figure 2.4).

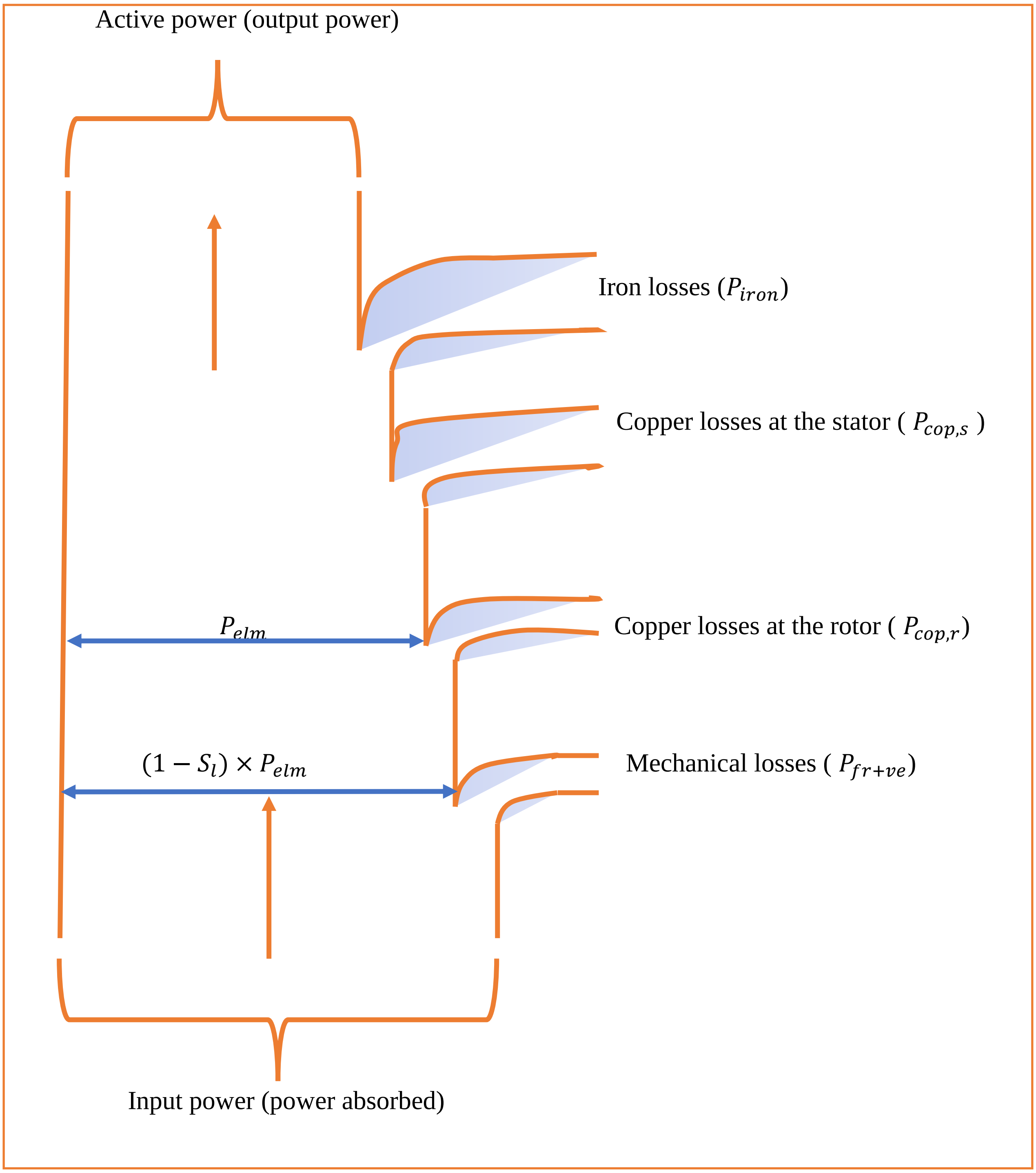


Figure (2. 4) : Generator power balance

P_{elm} is called electromagnetic power (or air gap power). It is transmitted to the rotor by the electromagnetic torque T_{elm} developed thanks to the rotating field.

$P_{elm} = T_{elm} \times \Omega_r$ ……………………………….. (2.12)

$\Omega_r = 2 \times \pi \times n$, being the angular speed of the rotating field [rad /s].

The electromagnetic torque is the same on the rotor and on the stator. But the speed of the rotor Ω_n is lower than that of the rotating field Ω_r:

$\Omega_n = (1 - S_l) \times \Omega_r$ ………………………….. (2.13)

Power is transmitted to the rotor with constant torque, but with a loss of speed. The mechanical power is therefore lower than the electromagnetic power:

$P_m = T_{elm} \times \Omega_r$ ………………………………… (2.14)

The difference ($P_{elm} - P_m$) is lost by the Joule effect in the rotor:

$P_{cop,r} = P_{elm} - P_m = T_{elm} \times (\Omega_r - \Omega_n) = T_{elm} \times \Omega_r \times S_l$ ………… (2.15)

$P_{cop,r} = S_l \times P_{elm} = 3 \times R_{rt} \times I_{rt}^2$ …………………………………… (2.16)

That's imply:

$P_m = (1 - S_l) \times P_{elm}$ .. ……………………………………………… (2.17)

And

$P_{elm} = \frac{3 \times R_{rt} \times I_{rt}^2}{S_l}$ ……………………………………………………… (2.18)

The useful power is obtained by removing from the mechanical power the mechanical losses P_{fr+ve}.

$P_{act} = P_m - P_{fr+ve}$ ………………………………………………… (2.19)

The expression of the useful torque is given by:

$T_{act} = \frac{P_{act}}{\Omega_n} = T_{elm} - T_{fr+ve}$ ……………………………………….. (2.20)

Where:

$T_{fr+ve} = \frac{P_{fr+ve}}{\Omega_n}$

The electromagnetic torque is proportional to the Joule losses in the rotor:

$T_{elm} = \frac{P_{elm}}{\Omega_r} = \frac{3 \times R_{rt} \times I_{rt}^2}{S_l \times \Omega_r}$ …………………………………………….. (2.21)

2.3. Doubly Fed Induction Generator (DFIG) and small hydroelectric power stations

2.3.1. Generalities

The Doubly Fed Induction Machine is very popular since it enjoys certain advantages over all other variable speed types, its use in the electromechanical conversion chain as a wind generator has grown dramatically in the past in recent years. Then, the energy converter used to rectify-wave the alternating currents of the rotor has a nominal power fractional of that of the generator, which reduces its cost by comparing to competing topologies. The asynchronous machine has a stator similar to that of conventional three-phase machines, most often made up of stacked magnetic sheets provided with notches in which the coils are inserted.

A doubly fed induction generator works by mechanically turning the rotors faster than in the case of synchronism. Its excitation system is generally supplied by the electrical network. It should be noted that for this reason, asynchronous machines are unable to restart a de-energized distribution system. More commonly, phase correction capacitors allow self-excitation.

Therefore, our project is about doubly fed induction generator and their control in the small hydropower plants. Small hydropower, where the power is generally less than 10MW, has enormous potential all over the world, which would allow it to make a significant contribution to future energy needs. According to UNIPEDE (International Union of Producers and Distributors of Electrical Energy), Table (2.2), small hydroelectric power stations in terms of the installed power are classified:

Table (2. 2) : Classification of small hydroelectric power stations

Hydroelectric power stations types	**Installed power [kW]**
Large hydroelectric power station	> 100 000
Medium hydroelectric power station	10 000 – 100 000
Small hydroelectric power station	2 000 – 10 000
Mini hydroelectric power station	500 – 2 000
Micro hydroelectric power station	20 – 500
Pico hydroelectric power station	< 20

Normally, hydraulic power stations are distinguished by their power in two main categories. "Large hydropower", a term grouping together the development of large powers, generally greater than ten megawatts, and "small hydropower" grouping together powers less than 10MW.

Particularly, many of the micro hydroelectric power stations, which have less than 500 kW of installed capacity, they use asynchronous generator or induction machine to generate power.

2.3.2. The principal advantages and limitations of an induction generator

Table (2. 3) : The principal advantages and limitations of an induction generator

Advantages of induction generator	**Limitations of induction generator**
Less expensive	Not well adapted for isolated and separate operation
More available	Consume more reactive power
DC field type of excitation voltage is not required	Impossibility for contributing to the reparation of system voltage level
Simple control	Low efficient

2.3.3. Basic concepts and review of previous works

The mechanical energy, available on the turbine shaft, is generally not directly usable on site. It is therefore necessary to be able to transform it into an easily transportable and usable form. This form is that of electrical energy. An alternator is a rotating machine that converts mechanical energy supplied by the turbine into electrical energy. The most common type of generator produces an alternative current, is known as an alternator [12]. An asynchronous machine rotates at a speed greater than the synchronism speed, which means that the rotational speed for a given frequency depends on the load:

$$N = (1 - s)\frac{f}{p} \qquad \text{……………………………………………………………….. (2.22)}$$

Where:

s : Slip

N : Rotational speed of the rotor [rpm];

f : Network frequency [Hz];

p : Number of alternator poles pairs.

Normally, the rotor speed is lower than the rotating speed of the magnetic field (created by the stator); hence the name of asynchronous machine. The Figure 2.5 shows an induction generator in small hydropower plant directly connected to the load island or consumers.

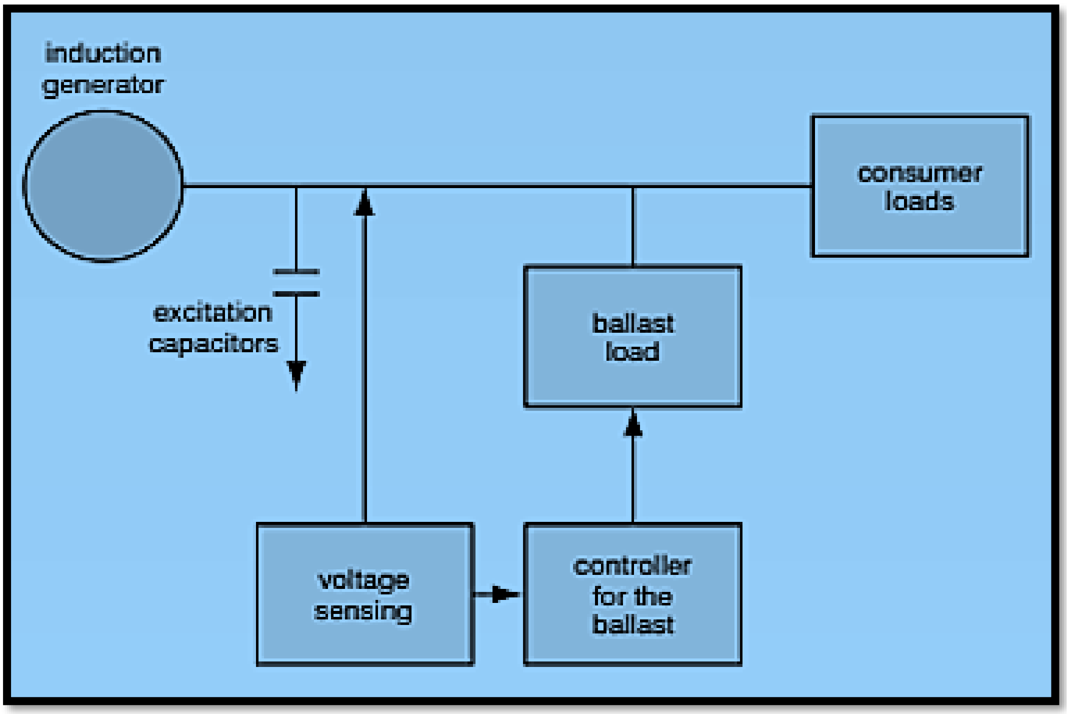


Figure (2. 5) : Micro-hydropower station scheme with asynchronous machine [13]

Much more integrated into a wind power system, the double fed asynchronous generator can operate over a wide range of wind speeds, and draw the maximum possible power from it, for each wind speed. Its stator circuit is directly connected to the electrical network. By the following figure (2.6), in variable-speed micro hydropower station, the DFIG (double fed induction generator) is still more used, their control system using frequency converters are carried out.

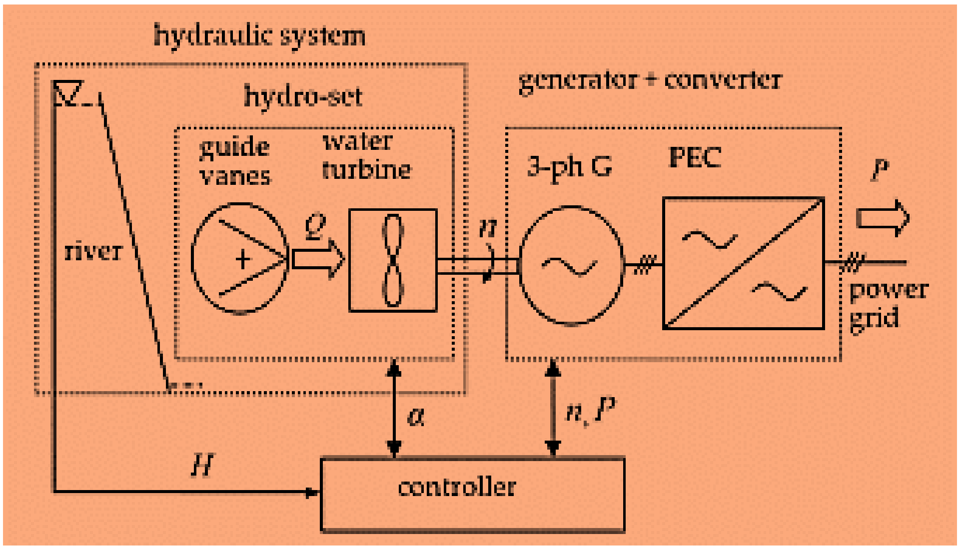


Figure (2. 6) : Control system in variable-speed micro hydro power station [14]

The double fed induction machine, abbreviated as DFIG, is a device using power electronics and making it possible to control the speed and the reactive power consumption of an asynchronous machine with a wound rotor. In the event of a reduction in speed, this arrangement has the advantage of not reducing the efficiency, the power being injected to the network. The Figure (2.7) is related to the stand-alone hydropower station with an asynchronous machine. The technique consists in placing a frequency converter between the electrical network and the supply of the rotor side. [15]

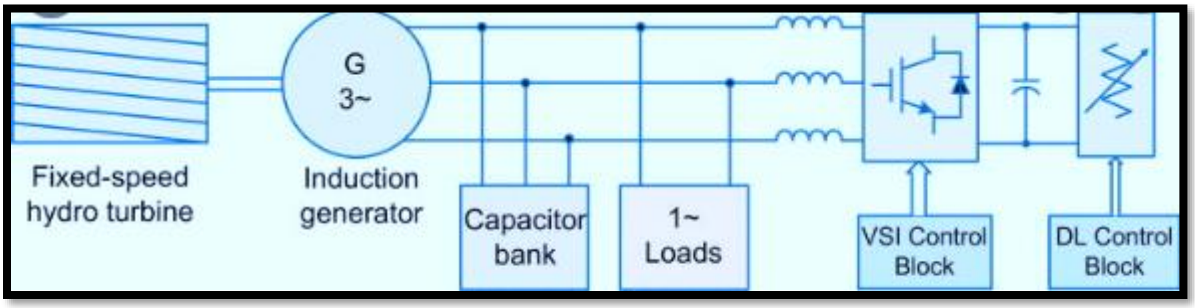


Figure (2. 7) : Small stand-alone hydropower station with an asynchronous machine [8]

2.3.4. Efficiency level of small generators

The curve (Figure 2.8) shows that the efficiency of small generators (Table 2.4) is high as long as its rated power is large.

Table (2. 4) : Efficiency level of small generators [16]

Nominal power [kW]	Best efficiency [%]
10	0.910
50	0.940
100	0.950
250	0.955
500	0.960
1000	0.970

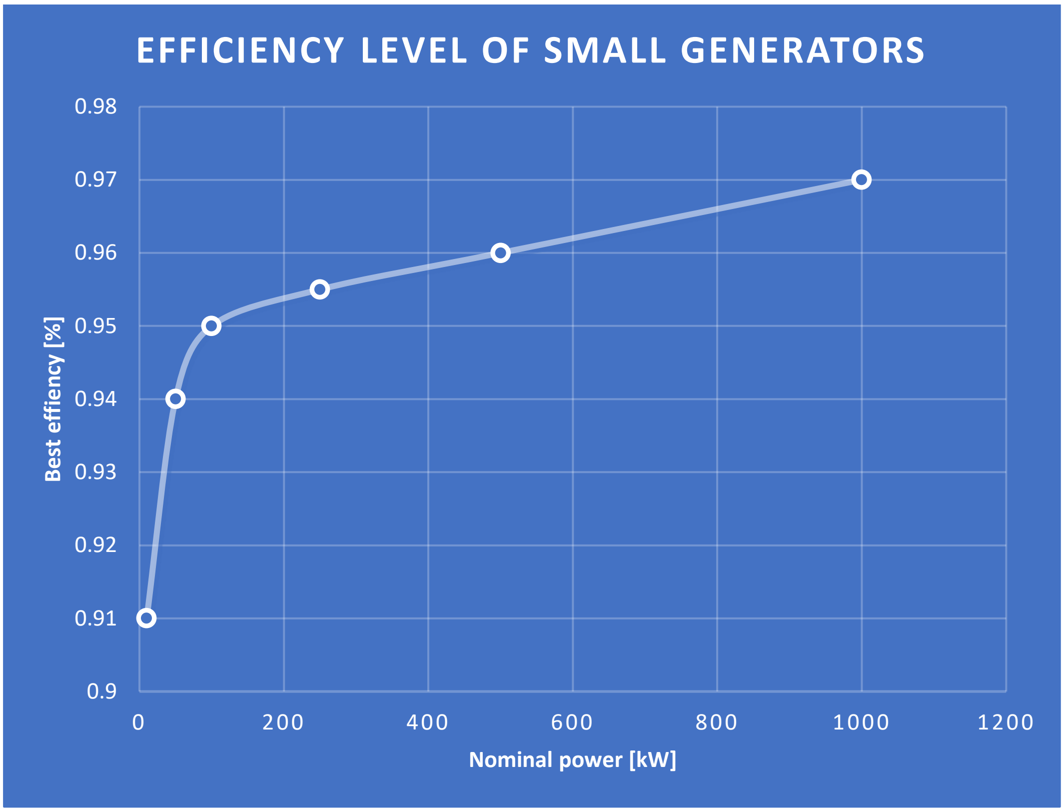


Figure (2. 8) : Efficient level of small generators

2.4. Power losses problem review

The asynchronous generator is characterized by simple design. It works by mechanically turning the rotors faster than in the case of synchronism. Unlike the synchronous generator, the asynchronous generator does not require any particular exciter. The required excitation current can be obtained either by reactive current taken from the network, or, in the case of island service, by capacitors connected in parallel on the stator winding. It should be noted that for this reason, asynchronous machines are unable to restart a de-energized distribution system. More commonly, phase correction capacitors allow self-excitation [17].

Three-phase asynchronous generators coupled in parallel to a rigid network drawing their magnetizing current of this network, either partially or completely (partial compensation will be done using capacitors) are currently manufactured up to a power limit of 10,000 kW. Higher powers are possible, both technically and economically. They are not limited for primarily electrical reasons, but for mechanical reasons linked in particular to the runaway speed [18].

The limit power of an asynchronous generator depends on several factors: first of all, it is necessary to know the importance of the reactive power that the network can provide to ensure the excitation in parallel operation and what part must be supplied by capacitors. Typically, capacitors should provide compensation for a power factor of 0.90 to 0.93. The rest of the reactive current should be provided by the network. Then, the induction generator speed may vary depending on the torque. This means that the generator machine will be suitable for increasing or decreasing its speed slightly according to the variation of the torque [19].

Thus, the stator is in direct connection to the network as long as the rotor is connected with a converter in three-phase mode through the intermediary of the slip rings. As a result, the power losses in the electronic converter could be reduced, compared to a system in which the converter must manage all the power, and the cost of the system is lower due to the electronics of partially rated power [20].

2.5. Power converter review

Power electronics (Figure 2.9) is one of the branches of electrical engineering, it concerns the study of the static conversion of electrical energy, the conversion is carried out by means of converters making it possible to change the form of the available electrical energy in a form suitable for supplying a load.

Power electronics is a discipline in which we seek to design and size electrical systems ensuring two objectives [21] :

i) modulate the transfer of power from an energy source to a receiver;

ii) guarantee the highest possible energy efficiency, by limiting maximum losses.

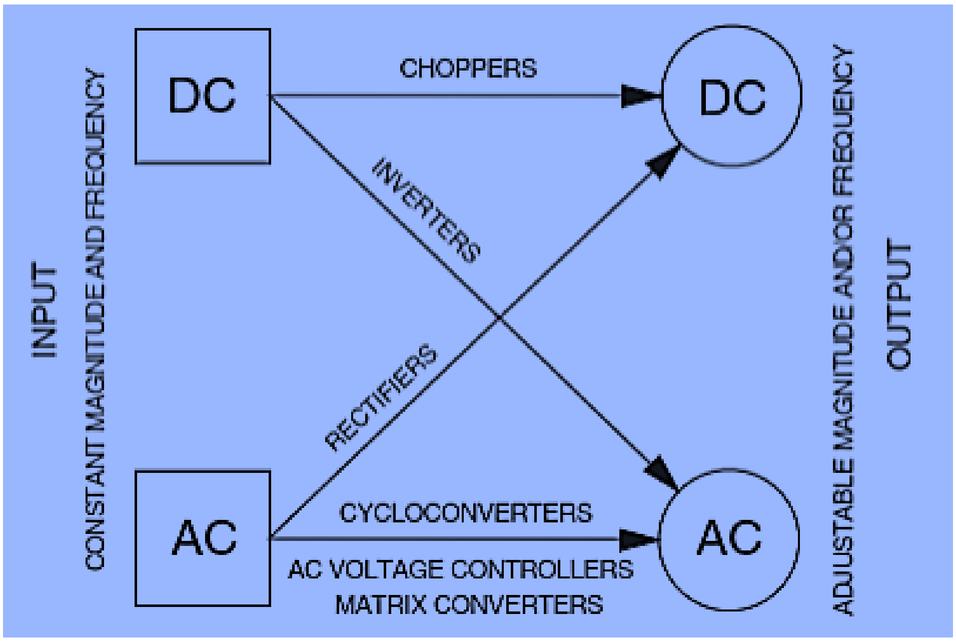


Figure (2. 9) : Electrical energy converting process with their associated electronics power [22].

The power electronic converters have an importance in all productions energy systems applications for achieving the highest efficiency with good performance. This power converter system performing could be achieved by the use of well measures of converter. Power loss, weight of converter, volumes, cost of components and rate of failure, are technical measures. If the system of converter is to be implemented, those measures could be effectively calculated [23].

Then, if we consider applications which are special, induction machine rotor could have wound system of three-phases in connection with three-ring. It is this kind of machine connected to the converters used with circuit of rotor which is used now for hydropower applications especially in variable speeds [24].

Utilization of the converters that are having statics frequencies in the connection of Grid and generation part is giving optimum solution for achieving a desirable generator speed [25].

By referring to the last), some of the associated electronics power converters on induction generators, in hydropower applications, could be inverters, known as kind of power electronics that converts direct current (DC) to alternating current (AC), the input voltage, output voltage and frequency, and overall power handling are all determined by the device's or circuitry's configuration; rectifiers that transform alternating current (AC) into direct current (DC) and pulse width modulation. The inverter handles the reversing process. The electricity is supplied by the DC source, not by the inverter [26],[27].

In addition, because of its low rotational speed, the turbine is connected to a gear box. A PMSM_permanent magnet synchronous system mounted on the same shaft provides excitation to a doubly fed induction generator (DFIG)**.** A pulse-width modulation (PWM) is a technique which help to reduce the intermediate (or average) energy provided by the electric system. The PWM, the VSI control block, the voltage sensing, … are also electronics devices which are helpful in control part of the energy system production in hydro power applications [28].

2.6. Research Gap

Electrical energy can be classified as the most important and flexible form of energy available nowadays, which is especially based on the improvement of power converters over the past decades. However, a power converter design is not a simple task: it always involves the many conflicting objectives to be minimized such as power losses, to ensure that multiple technological with thermal constraints have satisfaction [17].

For our project, we will have to contribute in minimizing of the highest starting currents, enhance the conditions of transmission of the power in the rotor circuits of asynchronous generators, we will design and optimize a power electronic converter with a suitable control system.

Asynchronous generators systems are now useful in different applications such as wind energy systems, mini hydropower generations systems, and in reducing application of high-pressure from gas streams systems to the lower pressure, because energy can be recovered with a simple controls system. Thus, when designing the power electronic converters, even for choosing the most efficient control system, we have to look seriously for those particular applications in order to pick the target [23].

2.7. Problem formulation

2.7.1. Introduction

In operation of hydropower generation systems, new opportunities are offered by improvements in power electronics and their control systems. The developments in performance system implies not only the usage of advanced control systems techniques, but also several converters even converter systems are integrated into the large system [29].

Power electronics or switching electronics concerns the processing and control of the transfer of electrical energy between a source and a receiver. It allows this energy to be converted in a given form (continuous, alternating, low or high voltage, etc.) into another. In this context, a strong specificity of this domain lies in the conversion yields sought, they should be typically close to 100 [30].

In our case, for increasing the efficiency of energy production system, we will choose and design a suitable power electronic converter which will be used in the area of connection between induction generator and network or island load.

2.7.2. Production of electromagnetic torque

When the stator is supplied by a balanced three-phase source, the instantaneous currents flowing in the three phases of the armature create a magnetomotive force F_{ms} which rotates at a speed:

$$\Omega_{ms} = {}^{\omega_{ms}}\!/_{p} \quad \text{…………………..} \ (2.23)$$

Where:

- ω_{ms}: Electric stator pulsation;
- p: Number of machine pole pairs;

On the rotor side, there is a three-phase winding connected to an AC source having a frequency f_r and which produces a rotating magnetomotive force F_{mr} at a speed $\Omega_{mr} = {}^{\omega_{mr}}\!/_{p}$ with respect to the rotor.

In order for the average torque to be constant as the rotor rotates relative to the stator, it is imperative that the magnetomotive forces remain synchronous. This would imply that the rotor itself must rotate at a speed of $\Omega_{ms}-\Omega_{mr}$. Any other speed produces a continual slip of the rotor poles relative to the stator poles. The average torque would then be zero and the machine would stop [31].

The resulting magnetomotive force F_{res} is the sum of the magnetomotive force F_{mr} and the magnetomotive force F_{ms}, in phasor notation we have:

$$\overline{F_{res}} = \overline{F_{ms}} + \overline{F_{mr}} \quad \dots\dots\dots\dots\dots\dots\dots\dots (2.24)$$

The resulting magnetizing flux in the air gap created by the resulting magnetomotive force has an effective value φ_m.

The amplitudes of the magnetomotive forces F_{mr} and F_{ms} are proportional to the currents which create them and to the number of turns of the windings:

$$F_{mr} = N_{mr} \times I_{mr} \text{ and } F_{ms} = N_{ms} \times I_{ms} \quad \dots\dots\dots\dots\dots (2.25)$$

Where:

- F_{mr}: Magnetomotive force at the rotor;
- F_{ms}: Magnetomotive force at the stator;
- N_{mr}: Number of turns of the windings at the stator;
- I_{mr}: rotor currents (that create magnetomotive forces at the rotor);
- N_{ms}: Number of turns of the windings at the rotor;
- I_{ms}: stator currents (that create magnetomotive forces at the stator);

Moreover, the equation (2.5) is a vector sum. The vector direction of the resulting magnetomotive force $\overline{F_{mr}}$ takes the direction of the vector -$\overline{I_{mr}}$.

This allows us to write:

$$N_{ms} \times \overline{I_m} = N_{ms} \times \overline{I_{ms}} - N_{mr} \times \overline{I_{mr}}$$

and then, that's imply:

$$\overline{I_{ms}} = \overline{I_m} + \frac{\overline{I_{mr}}}{m} \quad \dots\dots\dots\dots\dots\dots\dots\dots (2.26)$$

Where:

- m: Transformation ratio;
- I_m: Magnetizing current.

The electromagnetic couple exerted between the two magnetomotive forces represented by F_m and F_{mr} is the cross product of these:

$$T_{elm} = \overline{F_{res}} \Lambda \overline{F_{mr}} \text{ ....(2.27)}$$

If we take δ as the algebraic value of the phase of the current I_{mr}, the algebraic value of the torque is expressed by the equation:

$$T_{elm} = F_{mr} \times F_{res} \times \sin\left({}^{\pi}/_{2} - \delta\right) \text{ ....(2.28)}$$

Where:

- δ: Electric angle of current at the rotor

This figure (2.10) shows the vector diagram of the magnetomotive forces with the phase shift between F_{mr} and F_{res} in generator mode.

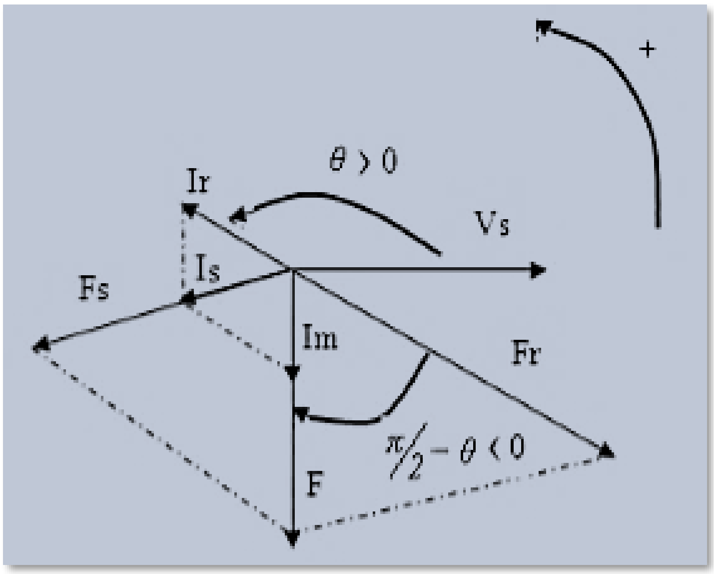


Figure (2. 10) : Magnetomotive forces vector diagram

Where:

- θ: is the electric angle of current at the rotor (δ);
- F_S: Magnetomotive force at the stator (F_{ms});
- F_r: Magnetomotive force at the rotor (F_{mr});
- F: resulting magnetomotive force (F_{res});

It can be seen that by acting on the amplitude and the phase of the current at the rotor Ir, we are able to control the electromagnetic torque and power factor. However, the control quantities accessible to the rotor are the voltage and the phase of the voltage at the rotor, therefore, we rather act on these latter as control quantities.

The flux vector $\overline{\emptyset_m}$ present in the air gap of the machine is the sum of the flux created by the stator windings $\overline{\emptyset_s}$ and the rotor flux $\overline{\emptyset_r}$ created by the windings of the rotating rotor.

The following figure (2.11) shows the different windings and fluxes present inside the structure of the doubly fed induction generator (DFIG).

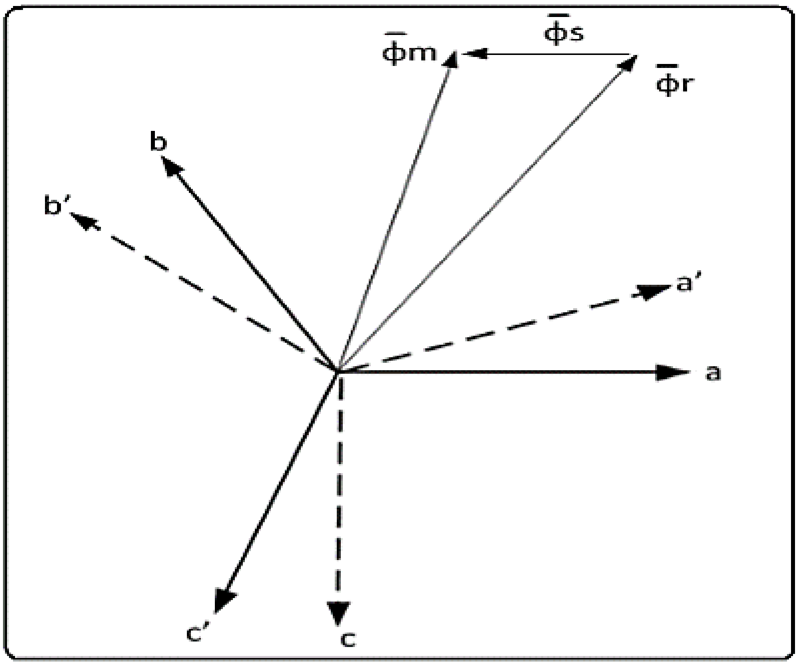


Figure (2. 11) : Configuration of windings and fluxes in a DFIG

Where:

- $\boldsymbol{a, b, c}$**:** the axes of the stator windings;
- $\boldsymbol{a', b', c'}$**:** the axes of the rotor windings;

In operation, the doubly fed induction generator requires torque on the machine shaft in the same direction as the direction of rotation of the rotating field F_{ms}. The effect of this torque causes the rotor poles to shift forward with respect to the stator poles and therefore the magnetomotive force of the rotor F_{mr} is ahead of the magnetomotive forces F_{ms} and F_{res} (Figure 2.7). The electromagnetic torque of the machine which is exerted on the rotor becomes a resistive torque in the opposite direction of the direction of rotation of the machine.

2.7.3. Induction generator: equivalent circuit and power transfer

We have already learned that an asynchronous motor becomes a generator when it is rotated above synchronous speed. Knowing the equivalent circuit below, Figure 2.12, the slip is given by [32]:

$S = \frac{N_S - N}{N_S}$ …………………………………… (2.29)

Where:

i) N_s: Synchronous speed
ii) N: Machine rotation speed

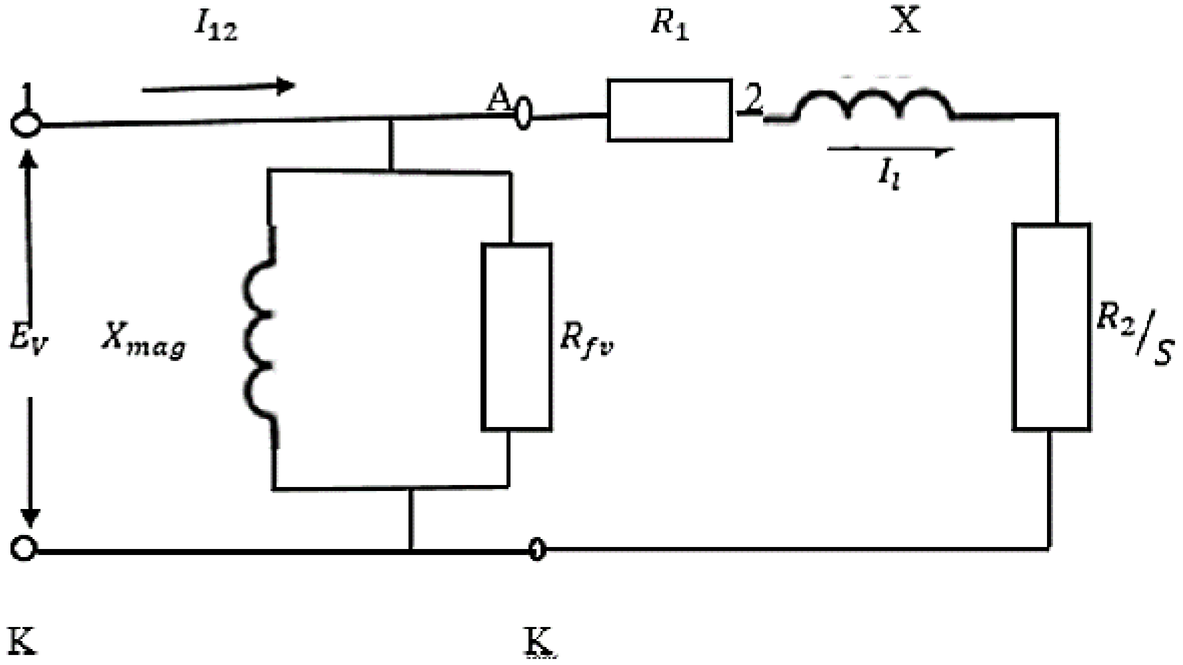


Figure (2. 12) : Equivalent circuit of the asynchronous generator

Based on the above figure, we have:

- Total resistance of the branch A-2-K:

  $R_{tot} = R_1 + \frac{R_2}{S}$ ……………………………… (2.30)

  Where:

  - ✓ R_1: Resistance value of R_1
  - ✓ R_2: Resistance value of R_2

- Impedance of the branch A-2-K:

  $Z_i = \sqrt{R_{tot}^2 + X}$ …………………………… (2.31)

  Where:

  - ✓ X: Reactance value of X

- Current of the branch A-2-K:

  $I_{12} = \frac{E_v}{Z_i}$ …………………………………….. (2.32)

  Where:

  - ✓ E_v: Voltage value

- Active power supplied to the rotor:

  $P_{s.r} = I_{12}^2 \times \frac{R_2}{S}$ ……………………………… (2.33)

- Joule losses in the rotor:

  $P_{jl.r} = I_{12}^2 \times R_2$ ………………………………. (2.34)

- The mechanical power supplied to the shaft is equal to $P_{s.r}$ plus the losses $P_{jl.r}$ in the rotor:

  $P_{mec} = P_{s.r} + P_{jl.r}$ …………………………… (2.35)

- Joule losses in the stator:

  $P_{jl.s} = I_{12}^2 \times R_1$ ……………………………….. (2.36)

- Losses in iron and by friction and ventilation:

  $P_{lf} + P_{lv} = \frac{E_v^2}{R_{fv}}$ ………………………………… (2.37)

- Active power transmitted to the line connected to the asynchronous generator:

  $P_l =$ Power supplied to the stator – losses:

  $= P_{s.r} - P_{jl.s} - (P_{lf} + P_{lv})$ …………………. (2.38)

- Reactive power absorbed by the leakage reactance:

  $Q_{2K} = I_{12}^2 X$ …………………………………….. (2.39)

- Reactive power absorbed by the magnetization reactance:

  $Q_{1K} = \frac{E_v^2}{X_{mag}}$ …………………………………… (2.40)

- Total reactive power per phase absorbed by the asynchronous generator:

  $Q_{tot} = Q_{1K} + Q_{2K}$ ……………………………… (2.41)

- Apparent power at terminals 1, K of the asynchronous generator:

$S_{app} = \sqrt{P_l^2 + Q_{tot}^2}$ …………………………….. (2.42)

- Line current:

$I_L = \frac{S_{app}}{E_v}$ ………………………………………… (2.43)

- Power factor at the terminals of the generator:

$\cos\varphi = {}^{P_l}\!/_{S_{app}}$ ………………………………… (2.44)

- Asynchronous generator efficiency:

$\eta_{gen} = \frac{useful\ electric\ power}{mechanical\ power\ supplied} = \frac{P_l}{P_{mec}}$ ………….. (2.45)

- Mechanical torque at the output of the asynchronous generator:

$T_m = \frac{P_{out}}{\omega}$ ………………………………………… (2.46)

Where: ω: angular velocity (rad/s);

The active power supplied by an asynchronous generator in an electrical network can be expressed by:

$P_{act} = \sqrt{3} \times U_l \times I_l \times \cos\varphi$ ………………………………. (2.47)

Where:

- U_l: Line voltage;
- I_l: Line current;
- $\cos\varphi$: Power factor.

The useful mechanical power to the shaft of an asynchronous generator is calculated according to the useful torque and the angular speed of the rotor (rad/s):

$P_{mec} = T_{sh} \times \omega$ …………………………………………… (2.48)

Where:

- P_{mec}: Useful mechanical power;
- T_{sh}: Useful torque;
- ω: Angular speed of the rotor;

To calculate energy efficiency, divide the amount of energy obtained (useful energy) by a machine, device or material by the amount of starting energy consumed (energy absorbed).

$$\eta_{en} = \frac{E_{out}}{E_{in}} \quad \text{………………………………………..} \ (2.49)$$

Interest in DFIGs continues to grow for various applications: as a generator for renewable energies. We conclude that the major interests of using this machine are:

- The converter linked to the rotor armature is sized for a fraction of the nominal power of the machine;
- Ability to operate over a wide speed range;
- Ability to control both torque and power factor;
- High efficiency.

The main drawback of this machine remains that of the presence of collector - brushes which makes it less robust and which requires regular maintenance.

The presence of the converter between the rotor and the network makes it possible to control the power between the stator and the network.

2.8. Chapter conclusion

The main purpose of a literature review is to summarize the state of the art or of knowledge in a field and for a period or a territory. Our project is about doubly fed induction generator (DFIG). In this chapter (2), Literature review was discussed, it was focused on asynchronous generators with their associated power electronics and control; the research gap of our work was carried out. The objectives of this chapter (2) of the project work are achieved.

CHAPTER 3. METHODOLOGICAL APPROCH AND SYSTEM MODELING

3.0. Introduction

In this chapter, methodological approach and system modeling, the process of systematic theoretical analyzes of the different methods used in control system of small hydropower generations using an induction machine, will be discussed. Our chosen method to achieve our goal and enhance the control system in such case, will be carried out with its specific discussion. The software to be used for results validation will be shown in this part of the project. Finally, the system modeling will be carried out and discussed.

3.1. Previous Methods

3.1.1. Direct-connection method

Renewable energy production systems are widely explored due to a major interest linked to sustainable development. From this part, the main previous method is then the direct-connection between generator and grid side or load island. This method has serious limitations and power losses in the production even transmission energy systems still not eliminated.

In fact, several problems due to this method could be listed as: close to the asynchronous generator, quality of power is deteriorated, limiting possible conditions of power transmitted control, and problems related to the highest of starting currents. Therefore, all this leads to the progressive and considerable decreasing efficiency of the system [33],[34].

3.1.2. Variable speed technology method

The rotor rim, in Figure 3.1, is used in variable speed technology in small hydropower applications in order to minimize the iron losses. Therefore, this type of direct connection method has also some advantages because it is possible to control the active and reactive power, it is possible for the generator to inject power instantaneously into the network by the use of storing energy in the mass rotating. At the end, it reduces abrasion of runners of the hydraulic turbines. However, the specific limitations listed in the direct-connection method above, remain unsolved. [35]

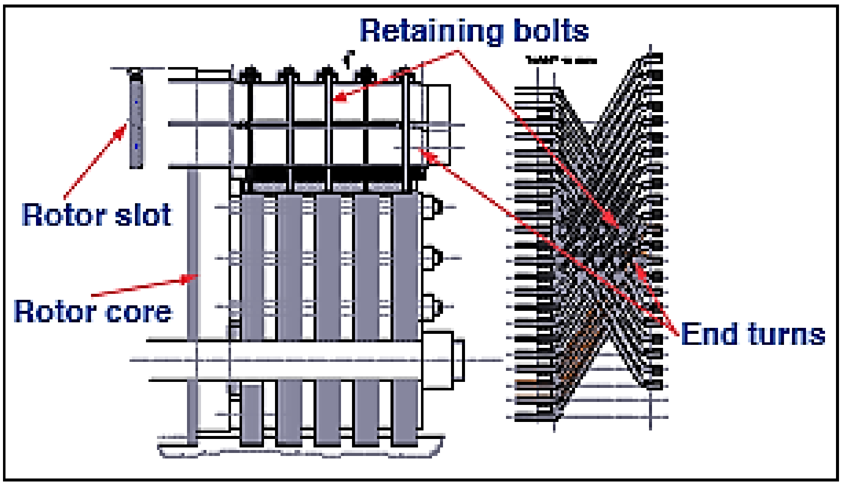


Figure (3. 1) : Rotor end winding support and press system [35]

3.1.3. Method of using a static frequency converter

This power electronic converter is included in the connection between the induction generator and grid side, in order to minimize the losses in small hydropower plant. This technic used in variable speed hydropower, is helpful in efficiency increasing. But some problems are still unsolved. Among them, we could list the start-up currents which are very high close to the induction generator, the possible conditions of transmission of the power which are limited [36].

3.1.4. Method of use of converter cascade for a DFIG

In a doubly fed induction generator (DFIG), the use of converter cascade such as cycloconverter was more helpful in small hydropower generations in [35] :

- Active and reactive power control;
- Control of the speed of turbo-generator machine;
- Control of the frequency of the production system;
- Control of the grid voltage.

Then, even if this method is efficient by considering all above reasons, it still has the limitations in power quality control and improvement, problems of transmission of power control and problems related to the very high start-up currents close to the generator.

3.2. Proposed method: use of suitable modern AC-DC-AC power converter

3.2.1. Background

For economic reasons, electrical energy is supplied by three-phase networks (three sinusoidal voltages out of phase with each other by $^{2\pi}/_{3}$) at the frequency of 50 H_z . Until the early 1970s, the shaping of the electric wave in order to adapt it to the needs was achieved by means of rotating groups.

Then, the performance of the semiconductor components of power electronics (diodes, thyristors, triacs, transistors) then made it possible to carry out such conversions. Static converters are devices with electronic components capable of modifying the voltage and / or frequency of the electric wave.

There are two types of voltage sources:

- The first one is DC voltage sources characterized by the value V of the voltage;
- The second one is Alternating voltage sources defined by the values of the effective voltage V and the frequency f.

There are four types of converters, the block diagrams of which are given in the following paragraphs:

- AC-DC converter: rectifier

  With many applications in power supply to direct current motors, charge batteries.

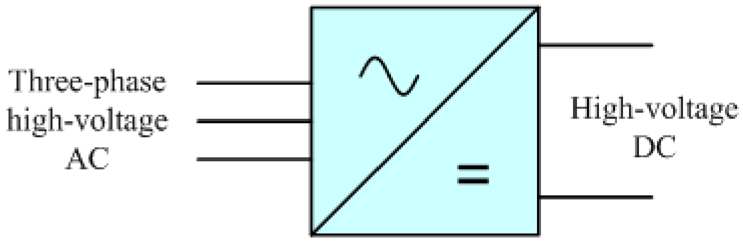
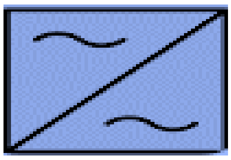


Figure (3. 2) : AC-DC power converter

- AC-AC converter: it is a dimmer when only the RMS value of the alternating voltage is modified, otherwise it is a cycloconverter; with many applications on production of alternating variable speeds (lifting, machine tool).



AC-AC Power converter

Figure (3. 3) : AC-AC power converter

- DC-DC converter: chopper

  With applications in control of direct current motors (variable speed); inverter switch functions or switching power supply.

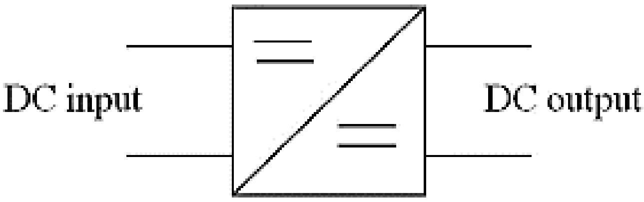


Figure (3. 4) : DC-DC power converter

- DC-AC converter: inverter
  With applications in production of alternating voltages, supply of autonomous electrical devices, protection against overvoltage's and network outages (informatics), control of alternating current machines.

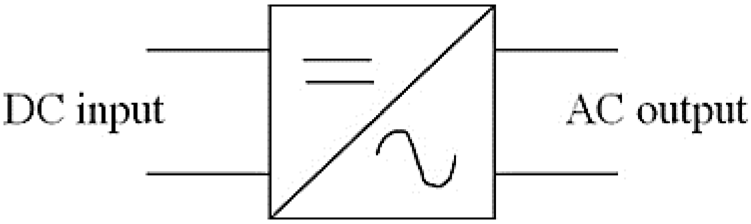


Figure (3. 5) : DC-AC power converter

Power electronic systems are assuming increasing importance in electrical energy engineering. Initially, the application of power conversion systems was limited to the use of uncontrolled rectifiers in the power supply systems of direct current devices or to the charging of accumulators representing a reserve of electrical power. The next step was to use controlled rectifiers in the excitation systems. The development of power electronics and electronic control systems has finally resulted in the gradual replacement of traditional excitation systems based on rotating machines by static systems.

Nowadays, the use of power electronic conversion systems to control the rotational speed of the hydraulic unit is an increasingly common practice. Speed regulation by means of power conversion systems is based on proper control of the unit load. For this purpose, AC-AC converters are used with a voltage and frequency on the generator side adapted to the parameters of the electrical network. At the same time, the converters ensure the control of the generator load so as to ensure the optimum operation of the unit. IGBT transistors are most often used as semiconductor power components in high power conversion systems.

Thus, to enhance the system efficiency in small hydropower plant, the proposed method is consisting of use of suitable modern AC-DC-AC power converter at the connection of induction generator and network side or power island part.

In order to achieve efficiently our goals, this method will be helpful and able to guaranteeing a suitable control system. This chosen AC-DC-AC electronic device with a specific control system will be designed and will help in reducing power losses in micro-hydropower applications which use an asynchronous generator.

3.2.2. Discussion

The AC-DC-AC power electronic converter constitutes of two main branches: the DC-AC converter which is an inverter that cooperates with generator part and the AC-DC converter which is a rectifier that deals with transmitting power energy from DC part of capacitor to the island or network sides. The introduction of this AC-DC-AC power converter in connection between induction generator and network or load island, with modern control system, will help really in achieving efficiently good results / profits in micro hydroelectric power generation systems.

Rectifiers are used to convert an AC power supply to DC. The output voltage and power can be controlled by the power components used (Thyristors). A rectifier, also called an AC / DC converter or Graetz bridge, is a converter intended to supply a load which needs to be supplied by a voltage and a current both as continuous as possible, from an AC voltage source. The power supply is, most of the time, a voltage generator.

As long as uncontrolled rectifiers, mainly made from diodes, are used when the output voltage does not need to be adjusted; controlled rectifiers whose output voltage can be variable include thyristors or assemblies of diodes and thyristors. Because of their high specific power, these rectifiers are always used at high power and when it is necessary to regulate or vary the electrical quantities at the output.

At low and medium power, the thyristor-controlled rectifiers are in the process of obsolescence and are advantageously replaced by the “cascading” of a rectifier, whether or not controlled, and of a DC-DC converter.

In small powers, the control of a field effect transistor or an IGBT is simpler than that of a thyristor, on the other hand, the operating frequencies of the choppers, which are today in the domain of 200 kHz, allow the size of the filtering components (inductors and capacitors) to be considerably reduced.

Finally, there are sinusoidal absorption rectifiers built using diodes, ballast MOSFETs or IGBTs which are used in order to improve the waveform of the alternating current consumed on the network side.

Inverters ensure the DC-AC power conversion. Supplied with direct current, they deliver one or more alternating voltages. The frequency of the alternating voltages can be varied and, in the most frequent case of pulse width modulation control, the value of these voltages. An inverter is an electronic power device that can generate any form of current including, for example, alternating current, from direct current.

Inverters are based on an H-bridge structure, most often made up of electronic switches such as IGBTs, power transistors or thyristors.

There are many types of inverters, the two main categories to differentiate are single phase inverters from three phase inverters. That is to say that the first category makes it possible to transform a direct voltage (supplied by a battery or at the output of a rectifier for example) into a sinusoidal voltage. The second type works in the same way but instead of transforming the voltage into a single sine, it generates three phase-shifted each between them 120^o that is $\frac{2\pi}{3}$ radians.

- **Filtering the output voltage**

The output voltage obtained after rectification is continuous. It has a DC component and an AC component, and therefore harmonics that need to be removed. To avoid the harmonics responsible for high frequency interference, a filter is used at the output of the rectifier.

We have the following formula:

$$C_{cap} = \frac{I_{Max}}{U_{max} \times f_{source}}$$

Where:

- C_{cap}: the capacitance of the capacitor;
- I_{Max}: the maximum output intensity;
- U_{max}: the maximum amplitude of the ripple;
- f_{source}: the frequency of the source,

3.2.3. Mapping of method to the problem

This is mapping the problem to the Method used, Figure 3.6 and Figure 3.7. In this part of the study project, the parameters in the method are having meaning in the specific problem being solved. The following figures show the AC-DC-AC power converter proposed between on one hand, the induction machine rotor and network side and on the other hand the AC-DC-AC power is located between induction generator and island part.

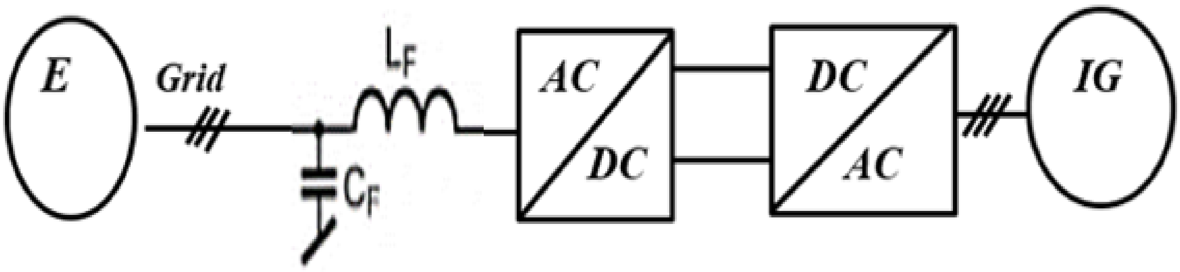


Figure (3. 6) : Diagram configuration of generator-converter-grid system

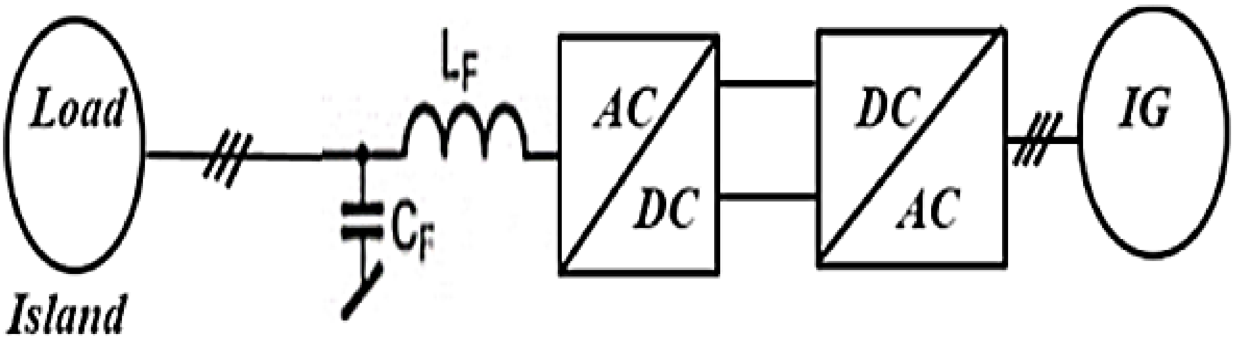


Figure (3. 7) : Diagram configuration of generator-converter-load island system

Thus, this procedure is preferable because it is a powerful and really effective tool for getting desirable good solutions. More importantly, the control system performances are very appreciated if they are compared to classical methods [20], [23].

The introduction of this AC-DC-AC power converter in connection between induction generator and network or load island, with modern control system, will help really in achieving efficiently good results / profits in micro hydroelectric power generation systems.

3.3. System modeling

3.3.1. Introduction

In electronics, systems modeling is used to predict the operation and performance of circuits or functions. This modeling relates primarily to: the system itself (the circuit), the external actions which are applied to it (the input signals). In this project, basically related to the power electronic converters in small hydropower plants which are using an induction machine, we need to have the model of our project as schematic diagram of system; this must allow us to achieve the expected results.

Then, two main models are shown below by considering two cases:

- The AC-DC-AC power converter is placed in the connection between asynchronous generator and network side (Figure 3.12);
- The AC-DC-AC power converter is included in the connection between asynchronous machine and island side (Figure 3.13).

3.3.2. AC-DC-AC power converter in the connection between induction generator and grid side

The following Figure 3.8 is established as the main model of our project when the doubly fed induction generator is connected to the grid side via an AC-DC-AC power electronic converter with its main control and protection systems. This function $P_w = f(\omega_m)$ is used to determine the power at the output of the hydraulic turbine and it can be done at any point of the shaft by considering the angular velocity $\omega_{m.}$ At this moment, it is easy to calculate the torque of shaft of the turbine $M^* = P_w/\omega_m$.

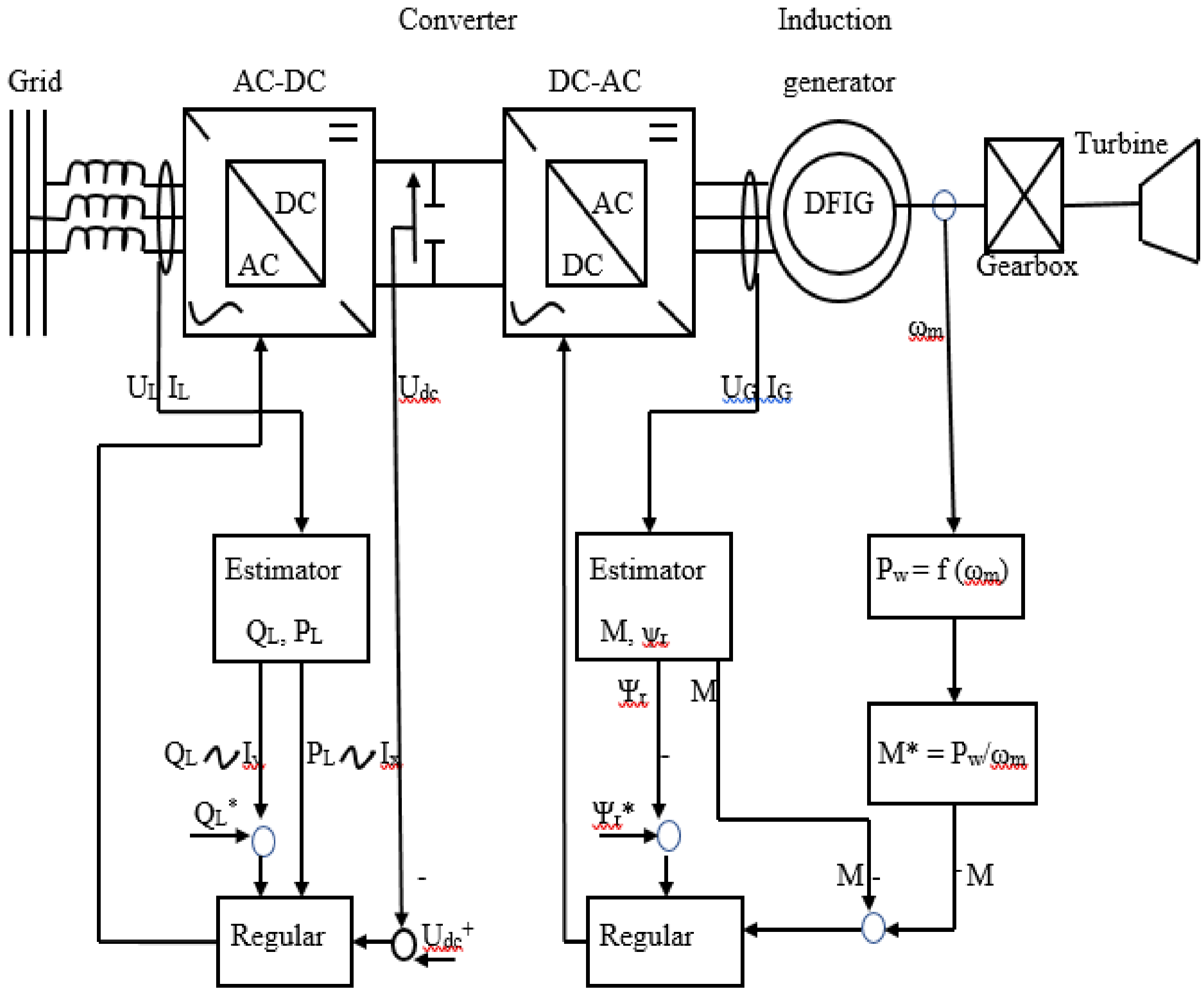


Figure (3. 8) : Schematic diagram model of the project in case of having AC-DC-AC power converter in the connection between asynchronous generator and grid side

The asynchronous generator, DFIG in this case, consumes reactive power form the grid or DC capacitor's circuit. The DC-AC power electronic converter connects the AC out put of the generator to the DC part from capacitor's bank. In the other hand, the AC-DC power electronic converter is allowing connection of DC link capacitor to the AC out put of the grid or network side and transmission of the power from DC to AC. The introduction of the estimators with systems of regulations at both sides (grid and induction machine rotor) is based on their effect of garanting and enhancing the power converter system protection. It is important to mention that the main control of this AC-DC-AC power converter is attributed also to the capacitors voltages regulation systems applied to the DC part side.

3.3.3. AC-DC-AC power converter in the connection between induction generator and island part

The following second model of our project, Figure 3.9, describes the power converter in the connection between doubly fed induction generator (DFIG) and load island part.

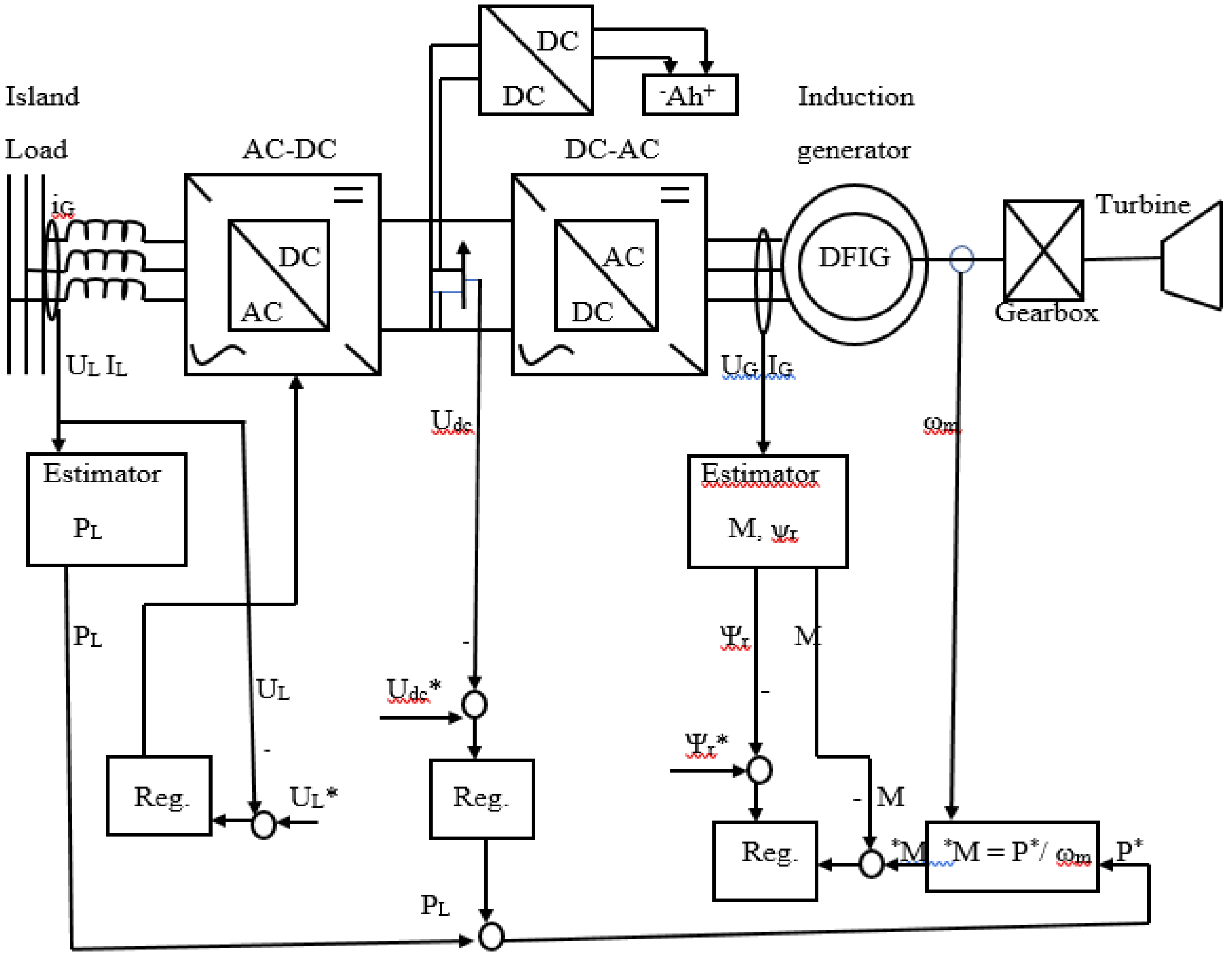


Figure (3. 9) : Schematic diagram model of the project in case of having AC-DC-AC power converter in the connection between asynchronous generator and load island side

The reactive power consumed by the DFIG in the system is provided always by the DC circuit. The regulation system of the transmission of power is also improved, as explained in the paragraph (3.3.2).

3.4. Proposed software

Matlab/simulink software will be used for results simulation, and also an experimental set-up will be conducted for results validation. Matlab is a software for performing numerical calculations. It was originally designed to facilitate the processing of matrices, but it is now used in all areas of science that require calculations.

This software has many interests [37]:

i) Infinitely faster programming for calculation and display;
ii) A very rich bookstore ;
iii) Possibility to include a program in C / C ++;
iv) Interpreted language: No compilation so no wait to compile;
v) Ability to execute code outside the program;
vi) Easy to understand and very readable code;
vii) A very well-done help.

This chosen software is really effective and more efficient for performing extensive data analysis.

3.5. Study for validation

A small hydroelectric power station is made up of a number of hydraulic, mechanical and electrical works, the design of which will depend on the type of development and local conditions. These components are made to work together. The regulation and monitoring devices coordinate and control the operation of the various organs of the small power plant and ensure the safety of the installations at the same time as a reliable energy production.

In order to validate the results, an induction machine rotor for a small hydropower plant with the nominal power of 20 kW, will be used in the results simulation.

3.6. Chapter conclusion

This chapter 3., Methodology and System modeling, was about the process of systematic theoretical analyzes of the different methods used in a specific study situation on the one hand. In small hydropower applications which are using a doubly fed induction generator, after carrying out a brief review of the previous methods, our proposed method to address the specific problems of our project was explained and discussed. On the other hand, the system modeling of our project in case of having either an AC-DC-AC power converter in the connection between small induction generator and network side, either this power converter in connection between induction machine and island part, were established and a specific discussion was carried out. MATLAB/Simulink software was chosen to be used in the results simulation and an experimental practical set-up will be conducted for results validation.

CHAPTER 4. RESULTS AND ANALYSIS

4.1. Introduction

In engineering, simulation is an efficient and economical means, commonly used to carry out preliminary and / or comparative studies, both at the design development stage, and during the normal operation of systems. Currently, several simulation tools, including MATLAB / Simulink, are used in industry and in academia. In this chapter, we will present the simulation of the results by use of MATLAB / Simulink and experimental set-up will be conducted as well as their analysis.

4.2. Results and analysis

Our project is dealing with small hydropower plants which use an induction generator, results simulation in Figure (4.1) and Figure (4.2), in the first step of start-up, are carried to show respectively the curve behavior of the voltages and currents in the direct connection between the generator and grid side.

i)

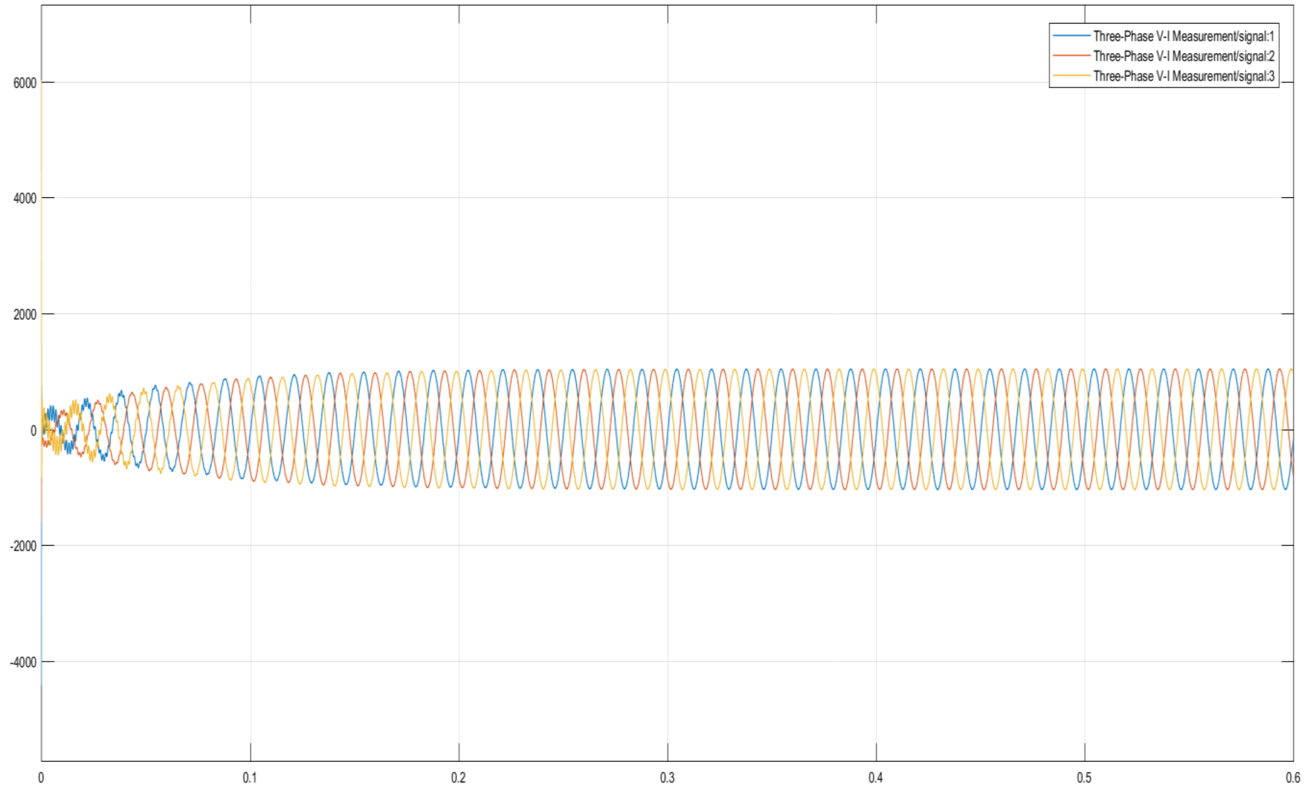


Figure (4. 1) : Low voltage result in the first step of start-up phase ii)

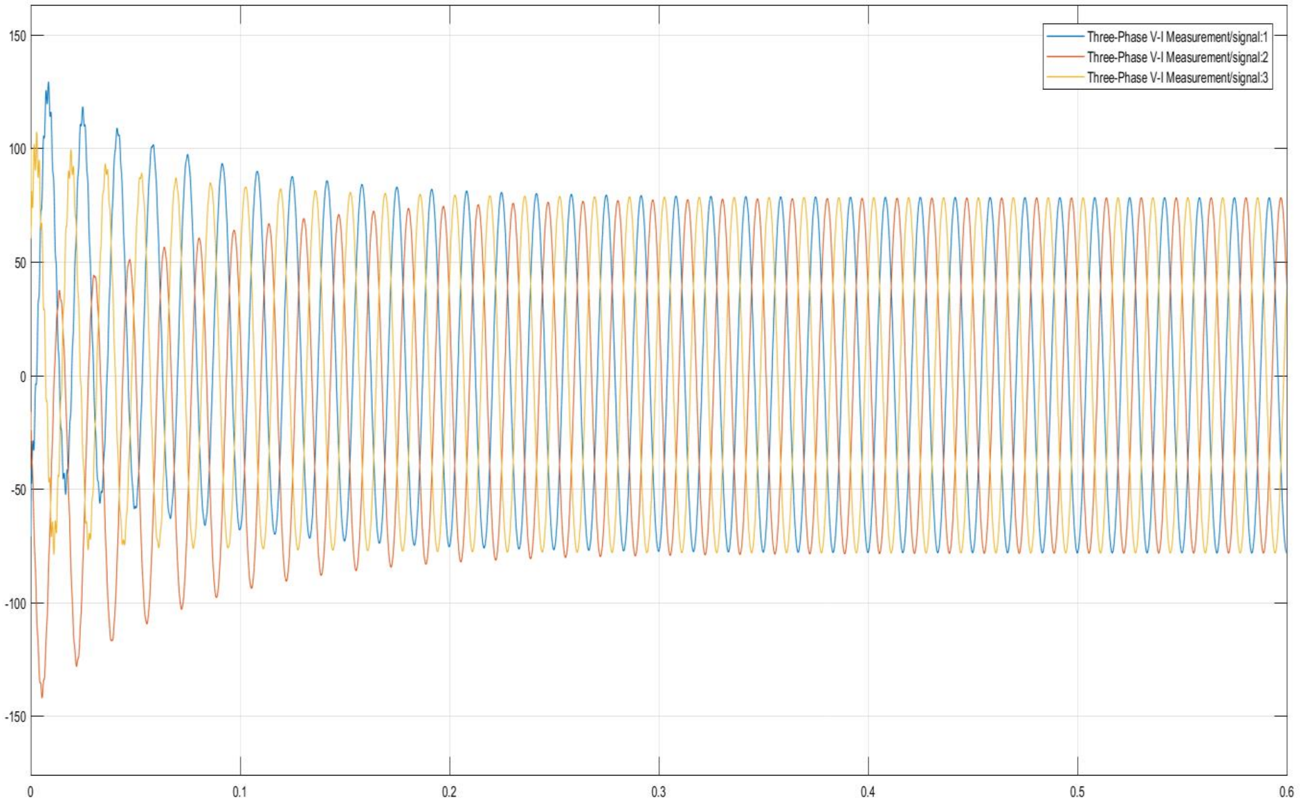


Figure (4. 2) : Highest starting currents results in start-up phase of the system

In this first step of start-up, we don’t have the power converter between the doubly fed induction generator and the grid. The simulation was done by considering the direct connection method and we have to analyze the results from the above two figures (4.1) and (4.2) respectively concerning the voltage and current behavior of the system.

- At the first interval of time: $t_0 = 0$ s to $t_1 = 0.1$ s : We have the very low value voltage on Figure (4.1) but it is increasing progressively. At this stage, we have the very highest currents in the same interval on Figure (4.2), which are decreasing as the time goes up.
- At the second interval of time: $t_1 = 0.1$ s to $t_3 = 0.3$ s : The progressive decreasing of the highest starting currents is still there. For the voltage side, it continues to increase until almost this time $t_3 = 0.3$ s.
- At the third interval of time between 0.3 s to 0.6 s : We have stabilization on both side, either on the voltage hand or either on the current evolution hand.

Therefore, when starting an asynchronous machine, the inrush current can reach several times the rated current of the machine. It is important to be able to limit this current.

iii)

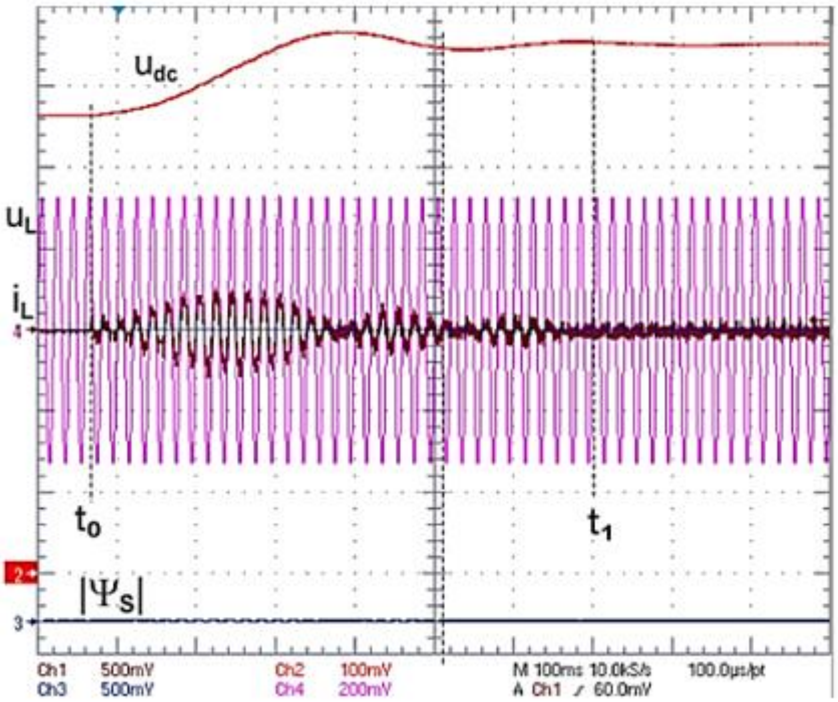


Figure (4. 3) : Highest starting currents result in first step of start-up

Results from experimental set-up in case we have the first step of start-up, that means when we have direct connection between an induction machine rotor and Grid.

- U_L is voltage line;
- The line current is i_L;
- The flux of the machine is given by Ψ_S.

At the initial time $t_{0,}$ we have high starting currents and it persist with a progressive decreasing before arriving at the time $t_{1.}$ In the first step of start-up, the capacitor's bank of battery pre-charging was fixed at 500 volts and after switching on the system of controls of the AC-DC rectifier, the battery charging has putted up to the value of the DC voltage of 600 volts.

At a certain time $t_{1,}$ we start having stabilization. If the application uses a drive or a starter, it is the latter which will adapt the voltages applied to the machine in order to limit this current. In the absence of a variable speed drive, there are several methods of limiting the starting current.

iv)

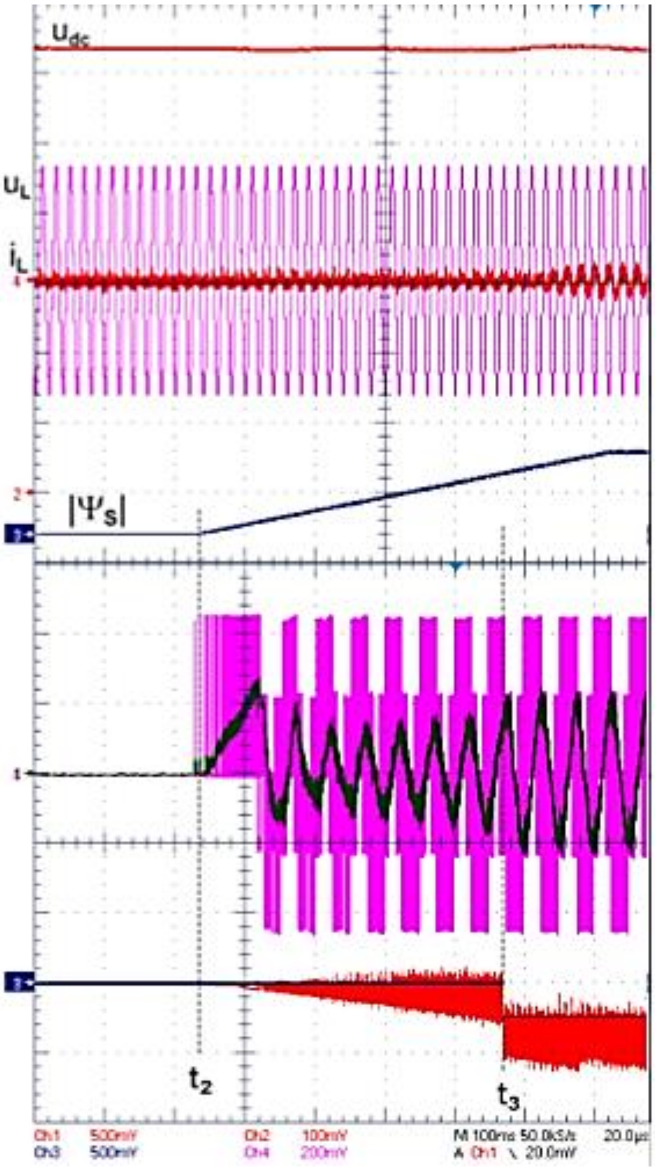


Figure (4. 4) : Laboratory results in the second step of start-up

In this secondary step of start-up, we have the converter structure characterized by three levels. The behavior of the torque coupling is given in this part of simulation. As the set value of the torque is given by this relation $M^* = P_w/\omega_m$, it has to be variable according to the variation of the angular velocity of hydraulic turbine. Then, at the first level of the above structure in Figure (4.4), the highest starting currents have limited by the use of suitable control system in the connection between generator and network side.

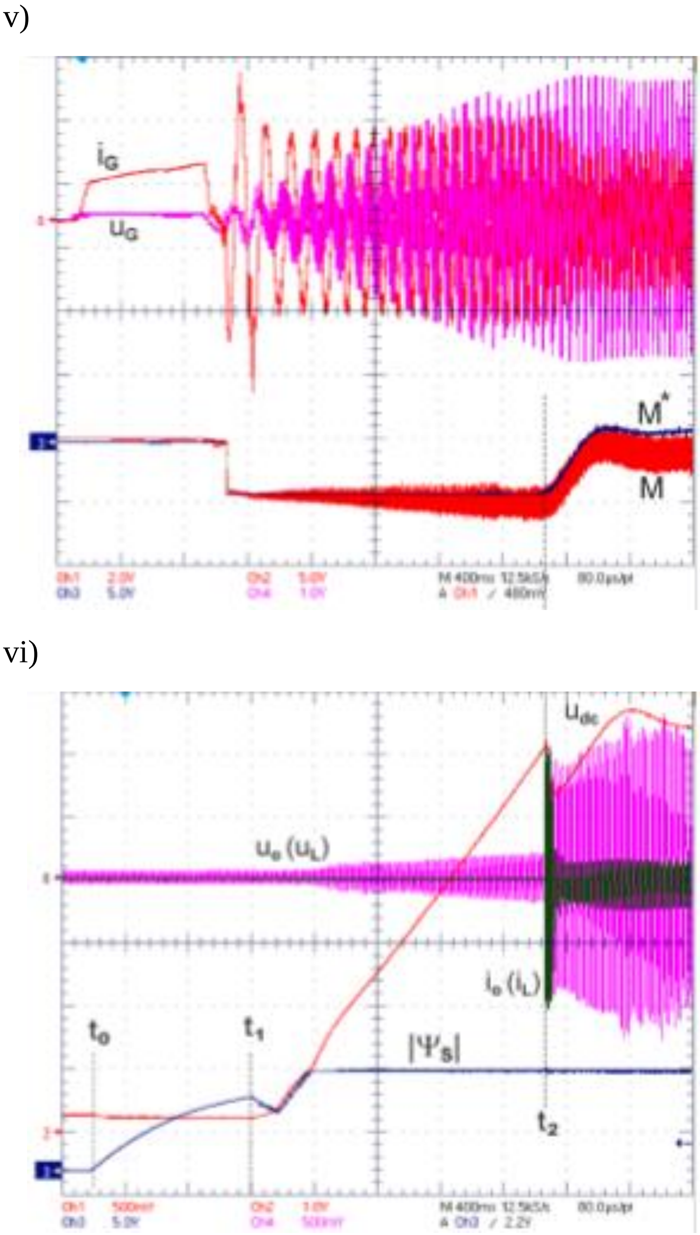


Figure (4. 5) : Laboratory results in the use of the power converter in load island mode

Where:

- I_G = generator’s current;
- U_G = generator’s voltage;

In this section in Figure (4.5) result, the AC-DC-AC power electronic converter is included into connection between doubly fed induction generator and the load island side, in the system of small hydropower generations. The DC-AC inverter cooperates with the induction machine rotor. It is in the last one, especially in the DC capacitor’s bank batteries that comes the main function of the DC voltages of system controlling. The load power demand (P_L) is covered by the suitable chosen power converter and it has the capability in preserving its own necessary value of the voltage $U_{DC}*$. Otherwise, the torque of the hydraulic turbine M* must be calculated based on load island P_l^*. DC-AC inverter controls the part of generator or induction machine rotor while the AC-DC is dealing with the island part.

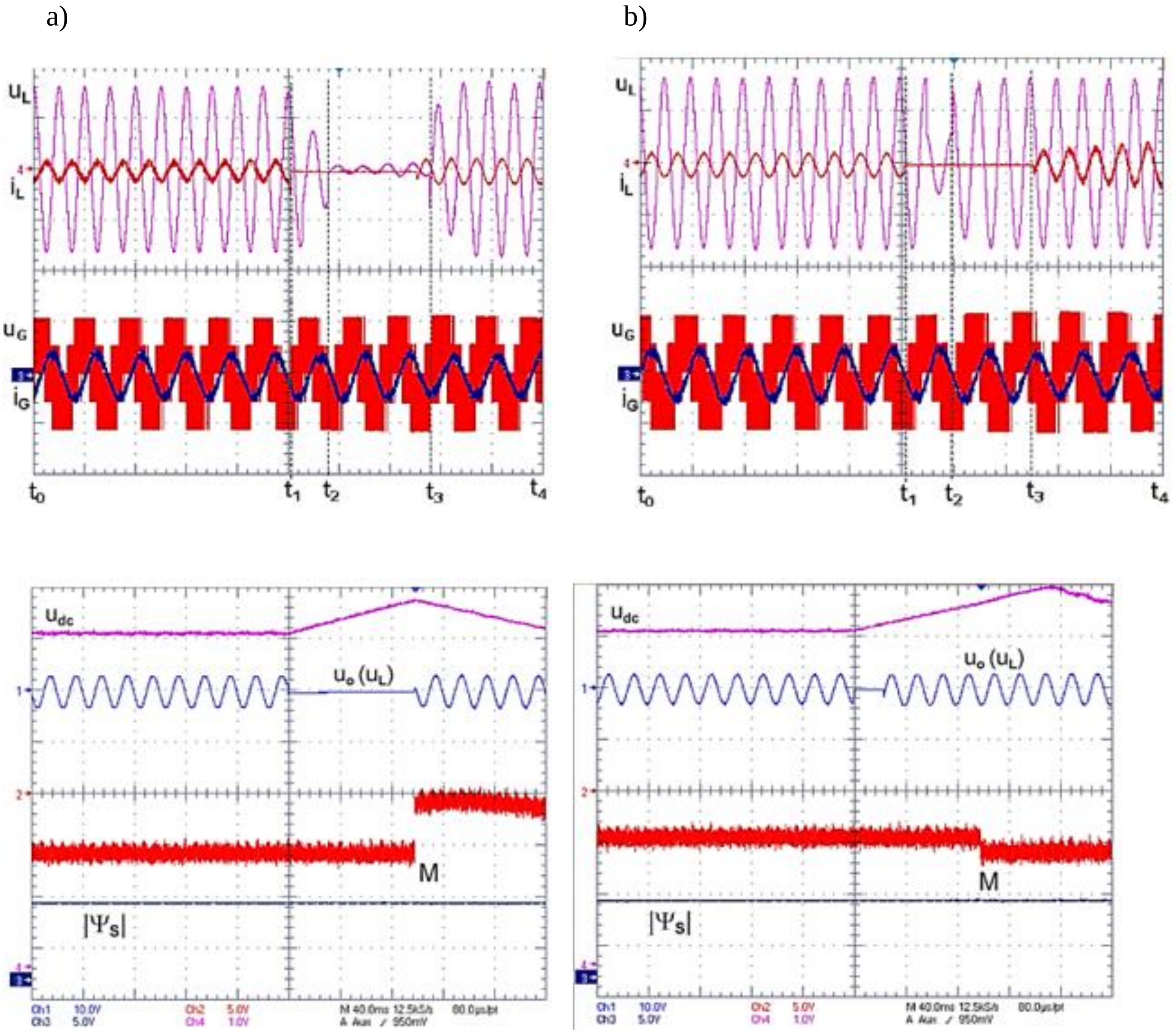


Figure (4. 6) : Results laboratory's from the DFIG cycle of switching connecting grid-load island or load island-grid;

(a) Results from cycle of switching of the induction machine. This is analyzed by considering Grid which is including power in the induction machine.

(b) In this part, we are considering the other side of induction machine which is injecting power into the load island.

Where:

- ✓ U_L: line voltage;
- ✓ i_L: Line current;
- ✓ i_G : generator current;
- ✓ u_G: generator voltage.

When there is drop in voltage from the grid side, the energy supply continues to transmit the required power directly to the consumers, as load island power. This is well possible by connecting the out put of the AC-DC rectifier with island side. The total harmonic distortion (THD) needed is less than 8% and the line voltage is molded in the AC-DC rectifier with the capacitors & inductances filters.

In the interval of the time: $t_0 – t_1$: the load torque at its maximum, which results from the output power of the hydraulic turbine, is received at the generator side.

In the interval of the time: $t_1 – t_2$: when there is a drop in voltage in case of induction generator cooperating with network side, Figure (4.6.a), the control system of the AC-DC rectifier is locked instantaneously and the W-switch is switched-off .

At the end, in the interval of time: $t_3 – t_4$: in case of having the induction generator cooperating with load island, the torque on generator was adjusted to the load’s demand by the control system.

In this interval : $t_1 – t_3$: There is no supply of power. There is a need to switch on and change also the configuration of the control. At this latter moment, the generator’s torque is adjusted itself to the load demand. In this interval of time, in switching-off mode, the DC voltage (U_{DC}) continue increasing until it reach over the value of 700 volts. At this point, the transmission of the power is done through the DC-DC power electronic converters to the accumulator. Finally, we have to mention that there is no variation either on the torque load and either on the flux of the generator in this switching-off period of the time, they are remaining constant.

4.3. Validation

By analyzing the results simulation and results laboratory, in case of having direct connection method, and in the other side with the specified power converter between the induction machine rotor and network side or island part, in small hydropower plants, we have the right to validate our method. The use of a suitable & specific AC-DC-AC power converter is an efficient method regarding all above considerations in this chapter 4.

4.4. Chapter conclusion

Our main objectives were focused on simulation of the study, Laboratory results and their analysis. Then, the solution of using AC – DC - AC power electronic converter was described and proved as a good method to be utilized in small hydroelectric generations which possess an induction generator. This method is helping to increase the efficiency of the production system because we have found that its control system has the capability of limiting the highest currents in start-up mode, it brings good contributions in the conditions of controlling of the power transmission either for active or reactive power characteristics and available quantities into the network side. This AC – DC - AC power electronic converter is able to minimize all interruption in power supply when we are in the switching-off mode. Finally, this detailed solution/method has the capacity to produce the energy for any lowest value of the hydraulic turbine's angular velocity.

CHAPTER 5. CONCLUSIONS & RECOMMENDATIONS

5.1. Conclusions

Small hydropower plants, due to their low power, their location along the water, their decentralized operating mode, their connection to the network, present notable differences from large installations. Most of small or micro-hydropower plants, they use an induction generator to produce electrical energy. An electromechanical generator converts the mechanical energy it receives at its shaft (hydraulic turbine) into electrical energy distributed to the consumer. It is about active energy. The asynchronous generator must be driven (turbine) at a speed greater than the synchronous speed; thus, the slip is negative. The asynchronous generator always consumes reactive power, because the stator winding is always the exciter winding. This reactive power will be supplied by the network or by a bank of capacitors.

Normally, the DFIG is a wound rotor induction generator. The stator windings are connected directly to the three-phase distribution network while the rotor windings are connected to bidirectional power to current converters. In this direct connection method, several problems which are causing progressive increasing of power losses, were carried out in this research project. To enhance the identified issues, our proposed method of using AC-DC-AC power converter, with its two main parts such AC-DC rectifier and DC-AC inverter, in the connection between induction machine rotor and network side, was discussed.

The results simulation, laboratory results and their analysis were carried out, all this give us the right to validate the method used. The MATLAB/Simulink software was used in the results simulation and an experimental practical set-up was conducted in the results validation. Then, in small hydropower plants which are using an induction generator, the use of the above specified power converter will be really helpful and allowing the progressive output power maximization.

5.2. Contributions to the knowledge

This final research project thesis has enabled me to achieve my goal of doing the optimization of the power converter for induction machine rotor in hydropower applications. For this, it was also the opportunity for me to review again the knowledge acquired during my master's training in renewable energies, such as the very important notions of energy & hydroelectric production, of electric machines and their control, advanced power electronics, renewable energy integration, … which, far from being limited to already established formulas, require apprehension and understanding of the energy phenomena concerned.

5.3. Recommendations

5.3.1. Adopting our results / findings

As there are a lot of hydroelectric energy sources available in our sub-Saharan countries of Africa, which are not exploited, for most of the case, normally those small or micro-hydropower generation will require a doubly fed induction generator in production process. Then, we recommend to the competent authority to consider this specified method in order to raise or improve more the profitability of the small hydropower plant.

5.3.2. Recommendation for further work

In this research work, we have to underline the aspect that optimization problems in hydropower generation, especially in small ones which are using a doubly fed induction generator, are still need to be addressed. For researchers, through this research project of dissertation, avenues for future reflection are left open to guide more in-depth research.

APPENDIX

To conduct the simulation of the study and the experimental set-up, the following details of data were used.

I. Asynchronous generator parameters

Table (5. 1) : Parameteters of the synchronous generator

Nominal power	20 kW
Angular velocity	145 rad/s
Nominal voltage	230 V
Nominal current	40 A

II. AC-DC-AC power converter parameters

Table (5. 2) : Parameteters of the power electronic converter

i)	Nominal power	20 kW
ii)	Frequency of switching	10 kHz
iii)	Nominal voltage	230 V
iv)	Value of capacitor	3 μF
v)	Value of inductances	11.5 mH

The type of this power electronic device is an Insulator Gate-Bipolar Transistor, which has a configuration of two times three levels.

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