CHAPTER 1

Introduction

1.1 Background

The world growing energy demand has contributed to the investment of huge amount of resources, economics and human, which is to develop the new technologies capable of converting all needed electric power. Moreover, the dependency on fossil fuels and the progressive increase of its cost lead to appearance of new cheaper and cleaner energy resources not related to fossil fuels. In the last decade renewable energy technologies have become more efficient, which have made it to attractive solutions, being cleaner and more environmentally friendly energy resource than traditional ones like fossil fuels, coal or nuclear. Renewable energy resources have been the focus for researches, and different families of power converters have been designed to integrate these types of supplies into the distribution grid. Beside the generation, electric power transmission needs high power in power electronic systems to assure conversion and the energy quality.

Hydroelectric power captures the energy released from falling water or reservoir. In the most basic terms, the water falls due to gravity, this causes kinetic energy to be converted into mechanical energy, and the useable form of electrical energy, respectively. Usually hydro turbines are optimized for the operating points defined by speed, head, and discharge. At fixed speed operation, any head or discharge deviation involves an important decrease in efficiency. The application of variable speed generation in hydroelectric power plants offers a series of advantages, based essentially on the greater flexibility of the turbine operation in situations where the flow or the head deviate substantially from their nominal values [1], [2]. Hydroelectric power generation supplies about 20 percent of the world electricity and is the most important renewable energy industry. The installed capacity of hydro-electrical power generation is approximately 700 GW with a production of 2600 TWh/year. The technically feasible potential of hydro power is 14000 TWh/year. Most of the feasible potential is in development countries in Africa, Asia and South America. The benefits of hydroelectric power generation are not only by environmental issues, but also the ability to meet moment to moment fluctuations, voltage control, energy storage, high efficiency and black start capability are valuable characteristics of hydroelectric power generation. The disadvantages of hydro-electrical power generation are the environmental impacts such as sedimentation, water quality and water ways for fish and the social aspects, for example the displacement of people living near dams [3].

In 1964, the first hydroelectric power plant was built in Thailand using dams (the Phumiphon Dam, Tak, Thailand) to store water at the most convenient location in order to best utilize power capacity. The potential of hydropower in Thailand is estimated at 15,155 MW. As of December 2002, The Electricity Generating Authority of Thailand (EGAT) produced 7,367 GWh of hydropower, which accounted for 6.6% of the total EGAT power generation by fuel type. However, hydropower resources are difficult to exploit due to the environmental impact on the resource areas a power project would entail. Therefore, future development of hydropower resources will be limited to a few small-scale projects which are considered most economical and environmentally friendly [4].

1.2 Generator systems

In a continued effort to reduce the cost, increase the reliability, and improve the efficiency of generator systems, a variety of generator system configurations have been developed. A classification of the most common configurations is given in Figure 1.1, where the prime mover from hydro/wind turbine can be generally classified into the fixed- and variable-speed generators. The fixed-speed generators employ a squirrel cage induction generator (SCIG) connected directly to the utility grid, the rotor speed of the generator is dictated by the grid frequency, and thus do not need any power converter during the normal operation. The main advantages of the fixed-speed generators are the simple, robust, reliable, low cost and low maintenance. The main disadvantages are relatively low energy conversion efficiency, high mechanical stress, and high power fluctuation into the utility grid, which yield voltage variation especially in weak grids [5].

The variable-speed generators are equipped with a synchronous or induction generator connected to the utility grid through a power converter. Therefore, the variable speed generators can achieve maximum energy conversion efficiency over a wide speed range. The converter system which serves as an interface must generally be provided between the constant frequency utility grid and the generator terminals. The variable-speed operation has the advantages over fixed-speed generator systems. It increases energy conversion efficiency, improves power quality, and reduces mechanical stress. However, the main disadvantages of variable-speed generator systems are the need of a power converter interface to control the generator speed, which adds cost and complexity to the control system and power losses due to the use of power converters [6].

In Figure 1.1, the variable-speed generator basic topologies can be classified into two types based on the power rating of the converter with respect to the total power of the system: reduced-capacity converter and full-capacity converter.

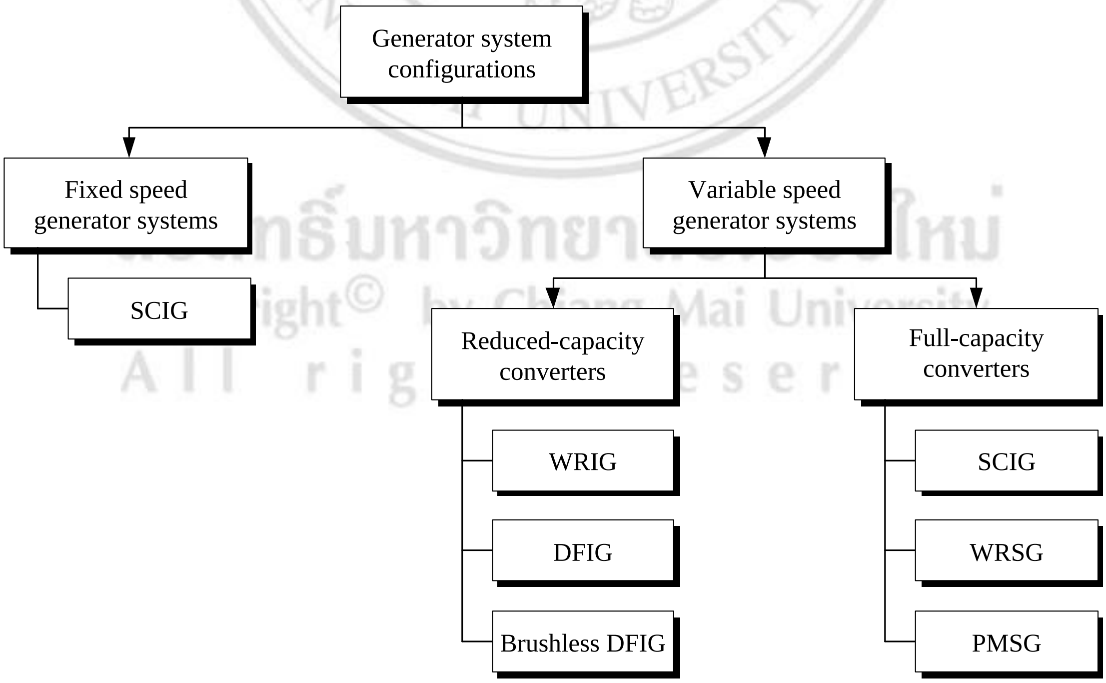

Figure 1.1 Classification of generator system configurations.

1.2.1 Generator systems with reduced-capacity converters

A typical block diagram of the doubly-fed induction generator (DFIG) system is shown in Figure 1.2. The configuration of this system connects the stator directly to the utility grid while the rotor is connected to the utility grid via reduced-capacity power converter. A back-to-back two-level voltage source converter system configuration is normally used. A back-to-back converter assures energy generation at nominal utility grid frequency and voltage independently of the rotor speed. The rotor-side converter controls the torque or active/reactive power of the generator while the grid-side converter controls the dc-link voltage and reactive power. The converters only have to process the slip power in the rotor circuits, which is approximately 30% of the rated power of the generator, resulting in reduced converter cost in comparison to the wind energy systems using full-capacity converters. However, the slip rings reduce the reliability and increase the maintenance [7].

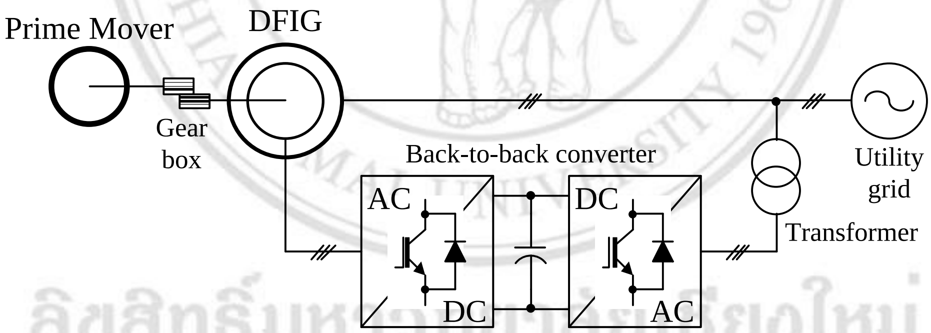

Figure 1.2 Variable speed generator system with reduced-capacity converter configurations.

1.2.2 Generator systems with full-capacity power converters

The variable-speed system with full-capacity power converter configuration for generators is shown in Figure 1.3. It shows such a system where the generator is connected to the grid via a full-capacity converter system [8]. Squirrel cage induction generators (SCIG), wound rotor synchronous generators (WRSG), and permanent magnet synchronous generators (PMSG) have all found applications in this type of configuration with a power rating up to several megawatts. The power rating of the converter is normally the same as that of the generator. With the use of the power converter, the generator is fully decoupled from the utility grid, and can operate in full speed range of generator. This also empowers the system to perform reactive power compensation and smooth utility grid connection. The main drawback is a more complex system with increased costs.

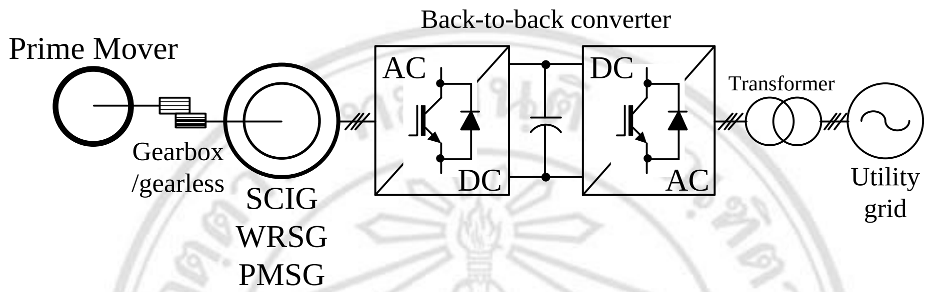

Figure 1.3 Variable speed generator system with full-capacity converter configurations.

1.3 Control scheme for doubly-fed induction generator

The most common electrical machines used for variable speed wind/hydro turbines are DC machine, synchronous machines, SCIG, and wound rotor induction generators (WRIG) [9]. All must use a power electronic converter interface for connecting to a fixed frequency, fixed voltage utility grid. With a wound rotor, when the rotor of a WRIG is connected to the utility grid through a back-to-back converter, usually it is called doubly-fed induction generator (DFIG). The system is applied for variable-speed wind power generator systems, which offers several advantages when compared with the fixed-speed generator. As seen from Figure 1.2, the stator of DFIG is directly connected to the utility grid, while the rotor is fed by the back-to-back converter. Since the converter only handles the slip power, it is rated about 30% of nominal generator power. By means of rotor power control, the system can work in a limited speed range of $\pm$ 30% of synchronous speed. Such a DFIG has received wide attention as a generator supplying power into a utility grid [9], [10]. Methods for controlling DFIG using back-to-back voltage source converter (VSC) have been widely reported [11]. The back-to-back VSC consists of rotor-side converter and grid-side converter that is “back-to-back” connected. Between the two converters a dc-link capacitor is placed in order to keep the voltage variations in the dc-link voltage. The back-to-back two-level VSC used in the rotor circuit of DFIG is the conventional method. These converters are characterized by low distortion currents both in the machine rotor and the utility grid. However, the back-to-back two-level VSC only suited for a low voltage and low power system application.

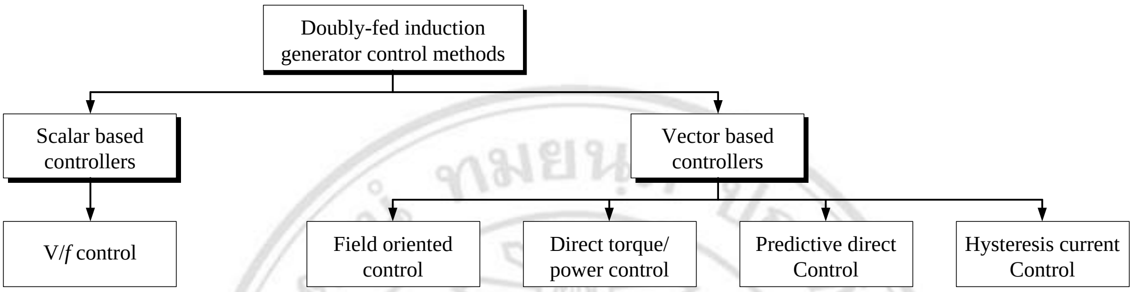

Figure 1.4 Classification of the DFIG control methods.

The classification of the DFIG control methods is shown in Figure 1.4. Different control strategies based on the back-to-back two-level VSC for DFIG has been introduced in the last few years. Traditionally, the techniques to control the rotor-side converter and grid-side converter of DFIG based variable speed turbines are the field-oriented control (FOC), the direct torque control (DTC), and the direct power control (DPC). The first FOC proposal for the DFIG, associated to a back-to-back converter, has been presented in [11]-[14]. Many researches then proposed improvements such as sensorless operation or new current regulators. After that, the nonlinear control techniques such as DTC [15] and DPC [16]-[18] have been proposed to overcome these deficiencies. The DTC and DPC techniques do not require current regulators, coordinate transformations, and specific modulations. DTC achieves better steady state and transient torque control conditions, but it presents the drawback of variable switching frequency behavior. However, switching frequency control can be performed using predictive control [19], [20]. Furthermore, [21] and [22] proposed enhanced hysteresis-based current regulators in the FOC of DFIG wind turbines.

The back-to-back two-level VSC for DFIG system has usually been employed as a robust and highly efficient solution, very popular mainly in low voltage levels. This topology has a number of features, including simple topology and modulation structure for the switching devices. However, it is well known that this converter presents some disadvantages which can be summarized as follows [23], [24].

1) The converter requires switch with relatively high switching frequency. The switching losses are much higher than the devices conduction losses. This applies in particular to high power converters.
2) The back-to-back two-level VSCs are based on voltage-source inverter technology, and LC filters are often required.
3) High *dv/dt* in the converter output voltage. Fast switching speed of switches results in high *dv/dt* at the rising and falling edges of the inverter output voltage waveform. It is particularly high for the two-level VSC employing series connected switches in a synchronous manner. Depending on the magnitude of the dc-link voltage and switching speed of the converters.
4) Harmonic losses. The two-level VSC usually operates at low switching frequency, typically around 500 Hz, resulting in high harmonic distortion in the voltages and currents. The total harmonic distortion (THD) in its output voltage, therefore often requires a large size LC filter installed at its output terminal.
5) Common-mode voltages. The rectification and inversion process in any converter generate common-mode voltage. If not mitigated, these voltages would appear on the machines, causing premature failure of its winding insulation.

1.4 Literature review

Numerous researchers have carried out extensive works on the techniques to control the rotor-side converter and grid-side converter of DFIG. Among all methods of control developed for the DFIG, the most widely used techniques may be classified into the indirect control techniques and the direct control techniques. The following presents a selection of achievements that have been of great inspiration for the author.

Pena, *et al*. [11] proposed the experimental implementation of a DFIG. The scheme consists of back-to-back two-level VSC connected between the rotor and stator of the machine. The converters are controlled using vector control techniques, which often used for the electrical control of DFIG. The control of grid-side converter using vector control techniques with a rotating reference frame aligned on the stator voltage vector has led to a decoupled control of the active and reactive power flow into the utility grid. It is based on the position of the line voltage vector and the relative orientation of the current vector. The vector control for the rotor-side converter has been embedded in an optimal tracking controller for maximum energy capture in a wind speed range operation. The rotor current is split into two current components in rotating reference frame. The quadrate component is used to regulate the torque and the direct component is used to regulate power factor or terminal voltage. These control strategies generally lead to good transient behavior and acceptable steady-state operation. They operate at a constant switching frequency, which makes the use of advanced modulation techniques possible. Therefore, it becomes easier to optimize conversion power losses or to simplify the filter design.

Gokhale, *et al*. [15] proposed DTC for DFIG fed by a back-to-back two-level VSC, which simplifies the controller design and reduces the parameter dependence of the system. The converter is connected to the rotor-side within a DFIG system, and hence the rotor flux is estimated. The rotor flux reference is calculated based on the required operating power factor. A switching vector was then selected from the optimal switching table based on the estimated rotor flux position, the torque and the rotor flux errors. Since the frequency of the rotor supply, which is equal to the DFIG slip frequency, could become very low, the rotor flux estimation method presents difficulties and its accuracy is significantly affected by the machine parameter variations. Furthermore, the calculation of the rotor flux reference according to the required power factor also requires the reference of actual parameters.

Abad, *et al*. [19] presented a new predictive direct torque control strategy of the DFIG. It is particularly designed to control the torque and the flux of the machine operate at a considerably low constant switching frequency, reducing the electromagnetic torque and rotor flux ripples, in order to provide good steady-state and fast dynamic performances. The DFIG is connected to the grid by the stator and the rotor is fed by a two-level VSC. Moreover, this control method allows a technique that reduces the switching power losses of the converter, which is the drawback of the hysteresis control in [12]. Experimental results show that the proposed DTC method effectively reduces the torque and flux ripples at low switching frequency, even under variable speed operation conditions for both motoring and generating modes at sub-synchronous and super-synchronous speeds.

Datta, *et al*. [16] proposed a method of direct decoupled control of active and reactive powers with high dynamic response in case of a grid connected DFIG fed by back-to-back two-level VSC on the rotor-side. The algorithm extends the switching logic of direct power control (DPC) to the rotor-side of a DFIG. The DPC algorithm uses only stator quantities for active and reactive power measurements and is inherently position-sensorless. It is computationally simple and does not incorporate any machine parameter. The algorithm can start on the fly and operate stably at synchronous speed.

Xu and Cartwright [17] presented a DPC strategy based on the estimated stator flux. Since the stator voltage is relatively harmonic-free with fixed frequency, a DFIG's estimated stator flux accuracy can be guaranteed. Switching vectors are selected from the optimal switching table using the calculated stator flux position, and the errors of the active and reactive powers. Thus, the control system is very simple, and the machine parameters' impact on system performance is found to be negligible. However, as the rotor power of the DFIG has not been considered explicitly, the tuning of the speed controller is complicated because insufficient information is available to the speed controller. Moreover, like a conventional DPC it has switching frequency that varies significantly with active and reactive power variations, generator operating with slip speed, and the hysteresis bandwidth of power controllers.

Xu, *et al*. [23] proposed a constant switching frequency DPC. In this technique, the control loop is the conventional PI current regulator with a nonlinear predictive current regulator. The proposed current regulator calculates the variation of the rotor current vector at the end of each fixed sampling period and based on the estimated error, the output voltage vector of the rotor-side converter is selected to eliminate the current errors at the end of the following sample period. Finally, the gating signals of the rotor-side converter are generated by a space vector modulation (SVM). This method is fully compatible with digital control platforms and shows a very fast transient response and an excellent robustness under various operation conditions. However, its performance depends on the accurate estimation of the machine parameters and it suffers from a complex control structure.

Cardenas, *et al*. [25] demonstrated an analysis and discussion of sensorless control of DFIG using a model reference adaptive system (MRAS). Estimated speed is provided by synchronization of estimated and measured stator flux, with stator flux estimation based on the stator and rotor currents. To achieve fixed amplitude of the stator voltage, a magnetizing current control is applied. It is tested only for this type of load system, which is a huge simplification in stand-alone operation of the alternating current generator. It has not been proven that the speed will be estimated correctly in case where nonlinear load would be applied.

Portillo, *et al*. [26] proposed the analytical strategy to model the back-to-back three-level neutral point clamped (NPC) VSC in high-power wind-energy applications. The model of different loads can be incorporated to the overall model. Both control strategy and load models are included in the complete system model. The proposed model pays special attention to the unbalance in the capacitor voltage of three-level NPC VSC, including the dynamics of the capacitor voltages. The proposed technique shows the direct influence of control signal on the dynamics of differences of capacitor voltages.

Ghennam and Berkouk [22] presented a novel space-vector hysteresis current control for a back-to-back three-level NPC VSC in the DFIG system. The proposed control technique controls the active and reactive powers delivered to the grid by the DFIG through the control of its rotor current. The three rotor current errors are gathered into a single space vector quantity. The magnitude of the error vector is limited within boundary areas of square shape. Moreover, it controls the neutral point voltage balance and maintains it to half of the dc voltage in converter by using the redundant inverter switching states.

1.5 Thesis objectives

From the mentioned problems, this research presents the concept of solving the problems as follows.

1) A modeling of DFIG using a back-to-back pulsewidth modulation three-level NPC VSC topology improves the waveform of voltage outputs, reduces the harmonic content compared to standard conventional converter, increases the power rating and decreases the stress across the switches.
2) Both rotor-side and grid-side converters are controlled with the developed direct power control techniques for DFIG based small hydro energy generation systems with constant switching frequency. Therefore, the key point of the proposed control is a correct and fast estimation of the active and reactive powers as well as fast PI controllers.

The main objectives of this thesis are as follows:

1) To develop, analyze and model the control strategy of the DFIG using the back-to-back three-level NPC VSC for small hydro turbine application.
2) To develop and design the direct power controllers of the rotor-side converter and grid-side converter for the DFIG system.
3) To analyze and verify the effectiveness of the proposed system on the laboratory set-up.

1.6 Outline of the thesis

This thesis is organized into five chapters as follows:

Chapter 1 gives a brief introduction of the background of this research. This chapter also reviews the state-of-the-art for doubly-fed induction generator and discusses the control schemes for doubly-fed induction generator. After that, the objectives of the thesis are presented and the related state of the art is studied.

In Chapter 2, the overview of hydroelectric systems and the full description of the experimental rig used is presented. This includes a discussion of the doubly-fed induction generator parameters, the power converters, the data acquisition system and digital signal processing used for the implementation of the control algorithm, and the interface circuits.

Chapter 3 discusses the basic structure and principles of three-level NPC VSC and presents simple modified unipolar carrier-based pulsewidth modulation (CB-PWM) strategy. Simulation and experimental results are presented to show the effectiveness of modulation strategy in the controlling converter.

Chapter 4 presents a DFIG system and mathematical model. The principles of the stator flux vector control are stated, which is using the rotor-side two-level VSC. Simulation results are shown to verify the control strategy.

Chapter 5 investigates a performance of improvement method of the DFIG using the back-to-back three-level NPC VSC with stator voltage vector controller. The modeling and experimental results show the efficiency of the DFIG is improved with the proposed method. Their controllers are analyzed and the designs are developed.

Finally, chapter 6 gives the conclusions and suggestions for future research.