Application of Wind Power Generation in Grid Connected Power System.

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ABSTRACT

This paper presents application of wind power generation in a grid connected multi-machine power system. An overview of wind energy technology and the current world wind energy scenario are presented. Various power generating units were considered in the prototype model of study. Merits and drawbacks of single and multi-machine systems, fixed and variable speed wind turbines were also presented. Focus was made on the wind-diesel system in the multi-machine model presented. The wind power impact on power quality was also discussed. In addition, the transmission system to shore (high voltage direct current - HVDC and high voltage alternating current - HVAC) were analyzed respectively. The process of producing hydrogen gas as a means of transporting and balancing wind power production, through an electrolyzer unit connected to the variable speed wind turbine in the offshore wind farm was analyzed. The variable speed drive mathematical simulink differential equations were also presented. Simulation analyses were carried out in power system computer aided design and electromagnetic transient including DC (PSCAD/EMTDC) to demonstrate the responses of the prototype model of the study.

(Keywords: variable speed wind turbine, wind energy, hydrogen gas, onshore network, offshore network.)

INTRODUCTION

Energy is an essential ingredient of socio-economic development and economic growth. Renewable energy sources like wind energy are indigenous and can help in reducing the dependency on fossil fuels [1]. Currently, about 87% of total energy is generated from fossil fuels (coal, oil, and natural gas), 6% is generated in nuclear plants, and the remaining 7% comes from renewable sources (mainly hydro and wind power) [2].

Unfortunately, the world has limited amounts of fossil fuel and nuclear power resources. According to current estimates, the natural uranium for nuclear power will last only about 50 years; oil will last no more than 100 years; gas, 150 years; and coal, 200 years.

Also, our overdependence on fossil and nuclear fuels is causing environmental pollution and safety problems, which are now becoming dominant issues in our society. The impact of the environmental pollution on global warming and the resulting climatic changes can have disastrous consequences in the long run. Hence, at this juncture, the world is turning more and more to environmental clean and safe renewable energy sources like wind, photovoltaic, and fuel cells.

The world has enormous resources of wind energy, and it has been estimated that tapping barely 10% of the wind energy available could supply all the electricity needs of the world [2, 3]. The recent technological advances in variable-speed wind turbines, power electronics, drives, and controls have made wind energy competitive with coal and natural gas power. However, one of the problems of wind energy is that its availability is sporadic, and, therefore, it needs to be backed by other power sources.

Photovoltaic systems have the additional advantage of being static and barely requiring repair and maintenance. However, photovoltaic power is typically five times more expensive than wind power, though there is tremendous research and development effort to develop low-cost photovoltaic panels for widespread terrestrial applications.

Solar power conversion efficiency is typically around 16%, and its availability is also sporadic. The primary fuel for fuel cell energy is hydrogen or a fossil fuel type like gasoline or methanol, with a reformer. Fuel cells are static and have high conversion efficiency of about 60%. However, they are bulky and expensive and have poor transient response in their current state. Fuel cells show tremendous promise for the future, particularly for electric cars, although a tremendous amount of research and development is needed to achieve this goal.

This paper addresses application of wind power generation in a grid connected multi-machine power system. An overview of wind energy technology and the current world wind energy scenario are presented. Various power generating units were considered in the prototype model of study. Merits and drawbacks of single and multi-machine systems, fixed and variable speed wind turbines were also presented. Focus was made on the wind-diesel system in the multi-machine model presented. The wind power impact on power quality was also discussed, in addition to the transmission system to shore (high voltage direct current - HVDC and high voltage alternating current - HVAC). The means of producing hydrogen gas for transporting and balancing wind power production, through an electrolyzer unit connected to the variable speed wind turbine in the offshore wind farm was analyzed. The variable speed drive mathematical simulink differential equations were also presented. Simulation analyses were carried out in power system computer aided design and electromagnetic transient including DC (PSCAD/EMTDC) to show the responses of the prototype model considered.

OVERVIEW OF WIND ENERGY TECHONLOGY

Wind is the indirect form of solar energy and is always being replenished by the sun. Wind is caused by differential heating of the Earth`s surface by the sun. It has been estimated that roughly 10 million MW of energy are continuously available in the Earth’s wind [4-6]. Wind energy provides an environmental friendly option and national energy security at a time when decreasing global reserves of fossil fuels threatens the long-term sustainability of global economy.

The wind turbine technology has a unique technical identity and unique demands in terms of the methods used for design. Remarkable advances in the wind power design have been achieved due to modern technological developments. Since 1980, advances in aerodynamics, structural dynamics, and micrometeorology have contributed to a 5% annual increase in the energy yield of the turbines [7-11]. Current research techniques are producing stronger, lighter, and more efficient blades for wind turbines.

The annual energy output for turbine has increased enormously and the weights of the turbine and the noise they emit have been halved over the last few years. More power can be generated from wind energy by establishment of many wind monitoring stations, selection of wind farm site with suitable wind generator, improved maintenance procedure of wind turbine to increase the machine availability, use of large capacity machine, low wind regime turbine, higher tower height, wider swept area of the rotor blade, better aerodynamic and structural design, faster computer-based machining technique, increasing power factor and better policies from government.

Even among the other applications of renewable energy technologies, power generation through wind has an edge because of its technological maturity, good infrastructure and relative cost competitiveness. Wind energy is expected to play an increasing important role in the future national energy scene [1, 3 and 12]. Wind turbines convert the kinetic energy of the wind to electrical energy by rotating the blades. Greenpeace states that about 10% electricity can be supplied by the wind by the year 2020. At good windy sites, it is already competitive with traditional fossil fuel power stations. With this improved technology and superior economics, experts predict wind power would capture 5% of the world energy market by 2020. Advanced wind turbine must be more efficient, more robust and less costly than current wind turbines.

WORLD WIND ENERGY SCENARIO

Details on the world wind energy scenario in November, 2011, based on the world wind energy association (WWEA) report [13] are as follows. Worldwide capacity reached 196,630 MW, out of which 37,642 MW were added in 2010, slightly less than in 2009.

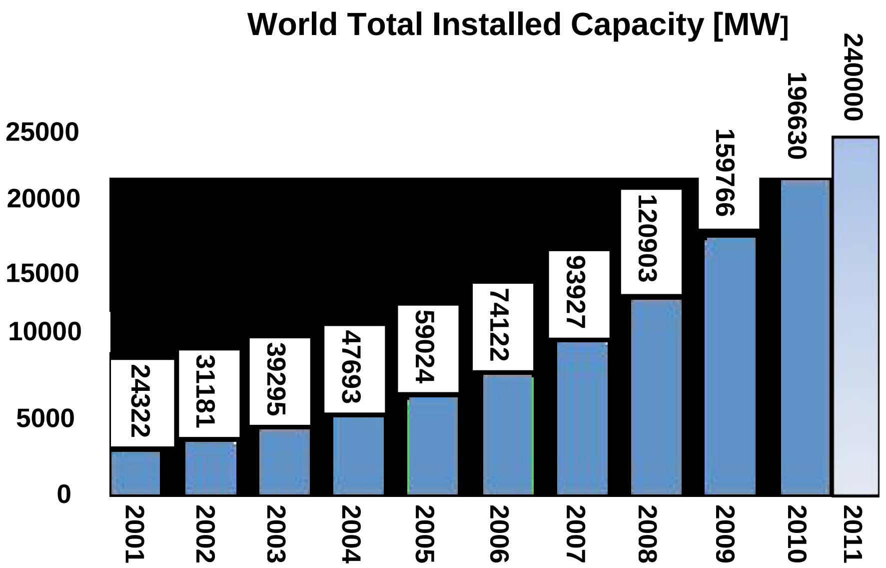

Figure 1: World Total Installed Capacity of Wind Energy [13].

Wind power showed a growth rate of 23.6%, the lowest growth since 2004 and the second lowest growth of the past decade. All wind turbines installed by the end of 2010 worldwide can generate 430 TWh per annum, more than the total electricity demand of the United Kingdom, the sixth largest economy of the world, and equaling 2.5% of the global electricity consumption.

The wind sector in 2010 had a turnover of 40billion Euro and employed 670,000 persons worldwide. China became number one in total installed capacity and the center of the international wind industry, and added 18,928 MW within one year, accounting for more than 50% of the world market for new wind turbines. Major decrease in new installations can be observed in North America and the USA lost its number one position in total capacity to China. Many Western European countries are showing stagnation, whereas there is strong growth in a number of Eastern European countries.

Germany keeps its number one position in Europe with 27,215 MW, followed by Spain with 20,676 MW. The highest shares of wind power can be found in three European countries: Denmark (21%), Portugal (18%) and Spain 16%). Asia accounted for the largest share of new installations (54.6%), followed by Europe (27.0%) and North America (16.7%). Latin America (1.2%) and Africa (0.4%) still play only a marginal role in new installations. In Africa, North Africa still represents large share of installed capacity, and wind energy plays hardly a role yet in Sub-Sahara Africa.

Nuclear disaster in Japan and oil spill in Gulf of Mexico will have long-term impact on the prospects of wind energy. Governments need to urgently reinforce their wind energy policies.

The World Wind Energy Association (WWEA) sees a global capacity of 600,000 MW as possible by the year 2015 and more than 1,500,000 MW by the year 2020 [13]. In the year 2010, the wind capacity reached worldwide 196630 MW as shown in Figure 1, after 159,050 MW in 2009, 120,903 MW in 2008, and 93,930 MW in 2007 [14-17]. Investment in new wind turbines saw a decline in many parts of the world. For the first time in more than two decades, the market for new wind turbines was smaller than in the previous year and reached an overall size of 37,642 MW, after 38,312 MW in 2009. China accounted for more than half of the world wind market 2010. Without taking into account China, the world market shrank by one third and decreased from 24,512 MW to 18,714 MW. Still and in spite of the slowdown, the installed wind capacity has been more than doubled every third year. In the year 2010, altogether 83 countries, one more than in 2009, used wind energy for electricity generation. 52 countries increased their total installed capacity, after 49 in the previous year. The turnover of the wind sector worldwide reached 55 billion US$ in 2010, after 70 billion US$ in the year 2009. The decrease is due to lower prices for wind turbines and a shift towards China [13].

The decrease in new installation outside China can be seen as a result of insufficient political support for wind energy utilization. In a paradox situation, more and more policy makers are declaring their support for increased use of wind energy, but such statements do not follow with the necessary political decisions. While the year 2009 had seen two major milestones – the first North American feed-in law in Ontario and the introduction of the first feed-in tariff in Africa –, the year 2010 did not bring comparable breakthrough decisions in national or international policies.

Especially in the USA, there is major regulatory uncertainty and not enough focus on renewable energy. Also in many developing countries there is still a huge policy gap and there is not yet enough stability and reliability in market frameworks, next to a lack of financial resources. In addition, the necessary international frameworks for renewable energy have not yet been established.

The year 2010 showed the second lowest growth rate, 23.6%, of the last decade. The growth rate is the relation between the new installed wind power capacity and the installed capacity of the previous year. Before 2010, the annual growth rate even had continued to increase since 2004, peaking in 2009 at 31.7%, the highest rate since 2001. The highest growth rates of the year 2010 by country can be found in Romania, which increased its capacity by 40 times. The second country with a growth rate of more than 100% was Bulgaria (112%). In the year 2009, still four major wind markets had more than doubled their wind capacity: China, Mexico, Turkey, and Morocco. Next to China, strong growth could be found mainly in Eastern European and South Eastern European countries: Romania, Bulgaria, Turkey, Lithuania, Poland, Hungary, Croatia and Cyprus, and Belgium. Africa (with the exception of Egypt and Morocco) and Latin America (with the exception of Brazil), are again lagging behind the rest of the world in the commercial use of wind power.

PROTOTYPE MODEL OF STUDY

Figure 2 shows the prototype model considered for this study. Two wind farms using fixed speed wind turbines (FSWTs) and variable speed wind turbines (VSWTs) are connected to the multi-machine power system. The FSWT wind farm is onshore, while the VSWT wind farm is offshore.
Some highlights about single and multi-machine systems are given below.

Single Machine System

- Has only one type of machine.
- Simple in structure.
- Not realistic case for study because is normally connected to an infinite bus, hence cannot be used to actually judge system performance.

Multi-Machine System

- Has different types of machines.
- Complex in structure.
- Gives a realistic scenario of a study and can be used to effectively judge performance of a proposed system or controller.

Also, some of the merits and drawbacks of FSWT and VSWT are itemized as follows.

Fixed Speed Wind Turbine (FSWT)

- Has fixed speed operation, thus the power captured is limited.
- Technology has limited ability to provide voltage and frequency control.
- Has superior characteristics such as brushless and rugged construction, low cost, maintenance free, and operational simplicity.
- Requires large reactive power to recover the air gap flux when a short circuit fault occurs in the power system.
- The installations of reactive power compensation devices to support the fixed wind speed generators increases the overall cost of the system.

Variable Speed Wind Turbine (VSWT)

- Has variable speed operation making it possible to achieve a high efficiency of energy conversion compared to constant speed operation especially in low wind speed areas.
- Ability to decouple control of active and reactive powers rapidly and independently by secondary excitation control. Thus, system tends to be more stable during network disturbances.
- The reduction of mechanical stresses and acoustic noise.
- Improvement of the power quality of the system without external reactive power compensation devices.
- The required capacity of the power converters for secondary excitation can be less than half for the case of a DFIG system, and thus the total cost decreases.

Wind-Diesel Systems

Figure 2 shows a larger AC coupled wind-diesel power system in sections B, C, and D respectively. A technically effective wind–diesel system supplies firm power, using wind power to reduce fuel consumption while maintaining acceptable power quality. In order to be economically viable, the investment in the extra equipment that is needed to incorporate wind power, including the wind turbines themselves, must be recouped by the value of the fuel savings and other benefits [18]. As the ratio of the installed wind capacity to the system increases, the required equipment needed to maintain a stable AC grid also increases, forcing an optimum amount of wind power in a given system. It should be noted that other diesel retrofit options do exist and these includes the use of other renewable technologies, such as biomass, or simply better control of the diesel generators [19].

A typical isolated diesel power supply system has the following characteristics [18-20].

- It has only one or few diesel generating sets. By using a number of diesel gensets of cascading size an optimal loading of diesel gensets may be obtained, thus increasing the efficiency of the diesel plant.
- The existing power system has quite simple controllers, often only the governors and voltage regulators of the diesel generators possibly supplemented by load sharing or self-synchronizing devices.
- The local infrastructure may be limited and there may be no readily available resources for operation, maintenance and replacement.
- Fuel is generally expensive and is sometimes scarce and prone to delivery and storage problems.
- The diesel engines provide adequate frequency control by the adjustment of power production to meet the load and voltage control by modifying the field on the generator.

In technical terms, an isolated power system for a large community that incorporates wind power (only sections B, C, and D in Figure 2) will be defined as a wind-diesel system when both the system layout and operation are significantly influenced by the presence of wind power in terms of:

- Frequency control, stability of system voltage and limited harmonic distortion.
- The operating conditions of the diesel generators, especially with regard to minimum load,
- Provisions for the use of any surplus wind power.
- Operation, maintenance and repair of any system components.

Wind-diesel power systems can vary from simple designs in which wind turbines are connected directly to the diesel grid with a minimum of additional features (as shown in Figure 2), to more complex systems [21, 22]. The important complication of adding wind power to diesel plants is that the production of energy from the wind turbines is controlled by the wind, meaning most turbines cannot control either line frequency or voltage and must rely on other equipment to do so as will be shown in the simulation results analysis. With only small amounts of wind energy, the diesel engines can provide this control function, but with larger amounts of wind energy, other equipment like the energy capacitor system (ECS), super magnetic energy storage (SMES) system, etc. are necessary.

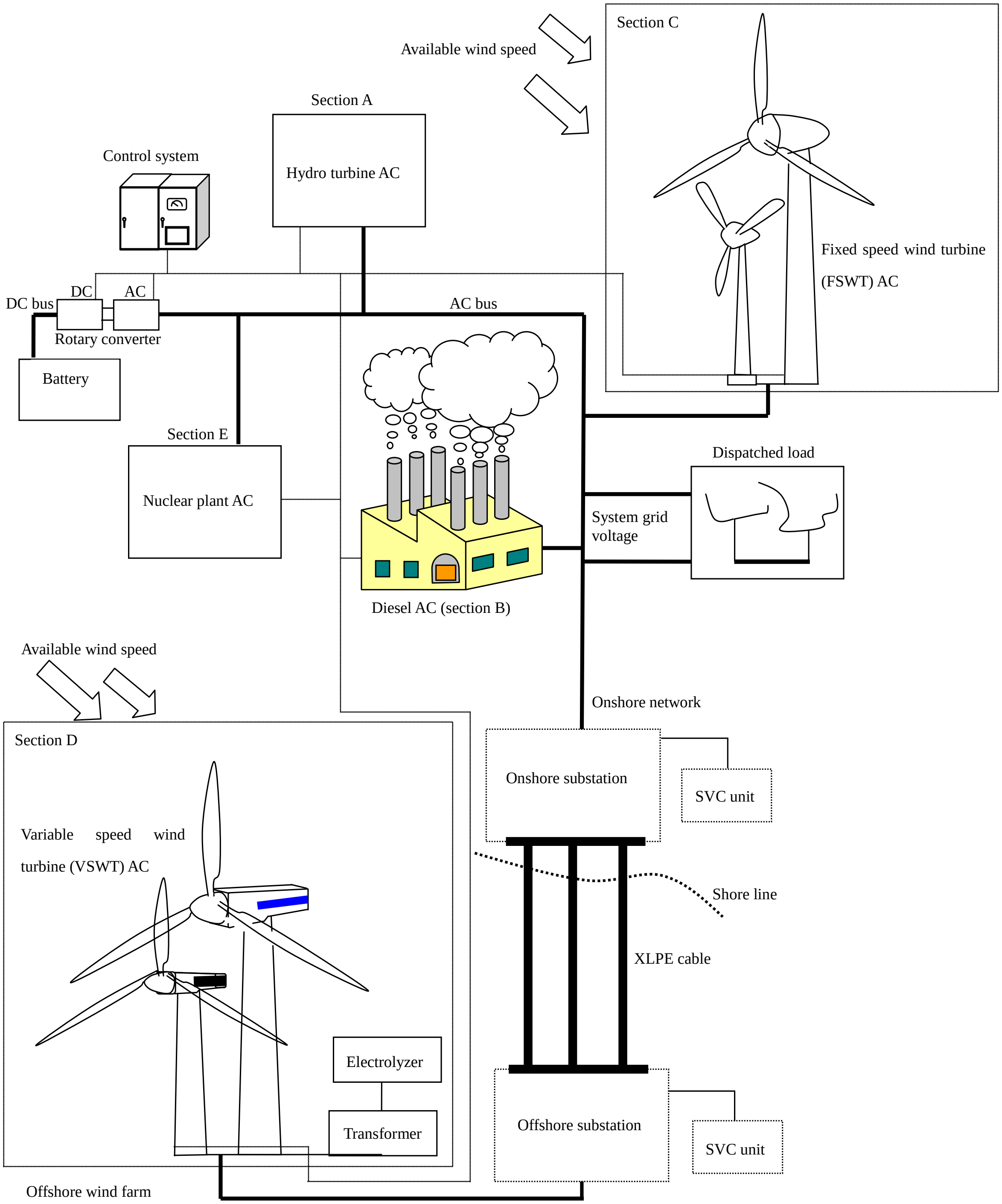

Figure 2: Prototype Model of Study.

Considering the above factors, two overlapping issues strongly influence system design and its required components. The first is the amount of energy that is expected from the renewable sources (known as system penetration), while the second is the ability of the power system to maintain a balance of power between generation and consumption (otherwise known as the primary use for energy storage).

WIND POWER IMPACT ON POWER QUALITY

In systems with turbines connected to the AC bus, the critical consideration is the variation of the power output from wind turbines and its impact on the operation of the power system and on power quality. This impact increases as the level of penetration increases [18]. The influence on power quality is mainly noted in the level and fluctuation of system voltage and frequency, the shape of the voltage signal or power harmonics and its ability to manage a reactive power balance. It is also important that the voltage of the distribution network remains constant, especially when interconnected to the wind turbines.

The transient and dynamic impact of wind turbines in single and multi-machine systems have been studied by the author in [23-40]. In all power systems that produce AC power, three critical parameters must be maintained:

- System frequency: the balance of energy being produced and energy being consumed. If more energy is being produced, the frequency will increase.
- Active or real and reactive power: depending on the types of loads and devices being used, a balance of active and reactive power must be maintained. In addition, some loads will require large amounts of reactive power, such as any inductive motor, and the equipment operating the system will need to provide this reactive power.
- System voltage: stable voltage from the source is required to ensure the proper operation of many common loads.

Different devices can be used to control different aspects of system power quality. The need for different devices will depend on the instantaneous penetration of renewable (i.e., wind energy that is expected). The higher the penetration, the more one must worry about how this will impact power quality and the more devices that must be added to the system to ensure high quality electrical power.

TRANSMISSION SYSTEM FOR OFFSHORE WIND FARMS

The transmission systems for offshore wind farms use either high voltage alternating current (HVAC) or high voltage direct current (HVDC) connections. For the HVDC connections, there are two technical options. The line commutated converter (LCC) based HVDC and the voltage source converter (VSC) based HVDC technology.

An HVAC transmission system consists of the following main components [18, 41, and 42]: an AC based controller system within the wind farm; an offshore transformer station including offshore reactive power compensation; three-core polyethylene insulation (XLPE) HVAC cables to shore, and onshore, and a static VAR compensator (SVC) unit as shown in Figure 2.

With an increasing distance to shore, reactive power compensation will be required at both ends of the cable (offshore and onshore). This reactive power would be provided by the SVC unit. The main disadvantage of the of the HVAC system is that with increasing wind farm size and distance to shore, load losses will increase significantly. Also, an increase in the transmission voltage level will lead to larger and more expensive equipment like transformer and cables. However, an increase in the voltage level is justifiable if an increase in capacity is required.

The advantage of line commutated converter (LCC) based high voltage direct current transmission (HVDC) technology is primarily for bulk power transmission over long geographical distances and for interconnecting power systems with different island systems [43].

A thyristor based LCC HVDC transmission system consists of the following main components [44, 45]: an AC based collector system within the wind farm; an offshore substation with two three-phase two-winding converter transformers as well as filters and either a static synchronous compensator (STATCOM) or a diesel generator that supply the necessary short circuit capacity; DC cables; and an onshore converter station with a single phase three-winding converter transformer as well as relevant filters.

The LCC HVDC technology requires comparatively large converter stations onshore and offshore, as well as auxiliary service at the offshore converter station. The auxiliary service at the offshore terminal require keeping strong AC system at the offshore converter in order to enable the operation of the line-commutated converters even during periods with no or very little wind.

The advantage of an LCC HVDC connection is that there are comparatively low losses in transmission over long distances. In addition, the higher transmission capacity of a single cable compared with HVAC or VSC based transmission can be an advantage for very large offshore wind farms.

Voltage source converter (VSC) based HVDC technology is gaining more and more attention. It is a comparatively new technology that has only become possible as a result of important advances in higher-power electronics, namely, in the development of insulated gate bipolar transistors (IGBTs). In this way, pulse-width modulation (PWM) can be used for the VSCs as opposed to thyristor based LCCs used in the conventional HVDC technology.

A VSC based HVDC transmission system consists of the following main components [41, 42]: an AC based collector system within the wind farm; an offshore substation with the relevant converters; DC cable pairs; and an onshore converter station. The system link of a VSC based HVDC does not require a strong offshore or onshore AC network, thus, it can even start up against a non-load network. This is possible because in a VSC the current can be switched off, which means that there is no need for an active commutation voltage. Besides, the active and reactive power supply can be controlled independently. Also, the VSC based HVDC connection is usually not connected to ground. Therefore, the system always needs two conductors or cables.

However, the total efficiency of the two converter stations of a VSC based HVDC system is less than that of a LCC HVDC. The advantages of a VSC based HVDC connection is the capability of four-quadrant operation, the reduced number of filters required, black-start capability and the possibility of controlling a number of variables such as reactive power, apparent power, harmonics and flicker when feeding the power system from a VSC [46, 47].

HYDROGEN

To avoid the spilling of renewable energy production, an energy storage medium needs to be incorporated into the generation system in order to allow flexible usage of the power generated. Hydrogen offers several interesting characteristics in this context [18]:

- It can be reconverted to electricity with a reasonably high efficiency if it used as fuel cells.
- It enables peak power production and load following, either from central installations or from virtual power stations, invariably, it offers decentralized generation capacity.
- It can constitute an alternative means of energy transport, for instance by using pipelines where electricity cables are undesirable and same time offering high energy density and low transport losses.
- It can be sold as industrial gas outside the electricity market, thus it reduces market pressure and develops alternative markets for renewable energy system.

Hydrogen is the element with the lowest atomic weight. The aspect of hydrogen that are most important in energy production are energy density, storage density, volume of storage, transportation energy effort, ignition limits, diffusion coefficient and explosion energy as per safety concerns.

The important role hydrogen plays in the context of renewable energy arises from the fact that it can be produced easily from water and electricity by the process of electrolysis. It can either be burned as a fuel as a substitute for gaseous fossils fuels or be converted to electricity in fuel cells in an electrochemical process that exceeds the efficiency of conventional electricity generation. Within certain limitations, hydrogen can be used for storing renewable electricity and can either be sold off as a product in its own or be reconverted to electricity.

In the prototype model of this study shown in Figure 2, hydrogen can be generated directly from electricity by using electrolysis. An electrolyzer is shown connected via a transformer to the smoothed output of the variable speed wind turbine. In an electrolytic solution, water is split into its components i.e. hydrogen and oxygen at two electrodes. The gases are produced separately at the electrodes and have a high purity. Electrolyzers can be operated at pressures between ambient pressure and 200 bars. The high pressure processes are more efficient but also lead to higher equipment costs and more complicated systems. However, they can feed a pipeline system directly without any additional compression. Electrolysis requires an input of desalinated and de-mineralized water.

SIMULATION ANALYSIS

Simulations were carried out using standard laboratory simulation tool called PSCAD/EMTDC^R. The simulink differential equations for the variable speed drive and some of the simulation results obtained based on the prototype model of Figure 2 are described in the subsequent subsections.

VSWT Mathematical Modeling

A doubly fed induction generator (DFIG) variable speed wind turbine (VSWT) machine is a wound rotor with back-to back converter in the rotor circuit. The rotor is supplied by pulse width modulator inverter, while the stator is directly connected to the grid. The rotor current exciting frequency is controlled as the wind velocity is changed. The frequency of output power is fixed at grid frequency, which is given as:

$$\omega_s = p\Omega_m \pm \omega_r \qquad \textbf{(1)}$$

Where ω_s is the grid electrical angular speed, Ω_m is the mechanical angular rotor speed, ω_r is the electrical angular speed of rotor variables, and p is the number of pole pairs. Equation (1) establishes the basis for variable speed constant frequency.

The mathematical equations of the DFIG in terms of stator, rotor voltages and flux are given as follows [48-50]:

$$V_{ds} = R_s i_{ds} - \omega_s \Phi_{qs} + \frac{d}{dt}\Phi_{ds} \qquad \textbf{(2)}$$

$$V_{qs} = R_s i_{qs} + \omega_s \Phi_{ds} + \frac{d}{dt}\Phi_{qs} \qquad \textbf{(3)}$$

$$V_{dr} = R_r i_{dr} - (\omega_s - \omega)\Phi_{qr} + \frac{d}{dt}\Phi_{dr} \qquad \textbf{(4)}$$

$$V_{qr} = R_r i_{qr} + (\omega_s - \omega)\Phi_{dr} + \frac{d}{dt}\Phi_{qr} \qquad \textbf{(5)}$$

The direct and quadrature stator and rotor flux components are given as follows [51]:

$$\Phi_{ds} = L_s i_{ds} + L_m i_{dr} \qquad \textbf{(6)}$$

$$\Phi_{qs} = L_s i_{qs} + L_m i_{qr} \qquad \textbf{(7)}$$

$$\Phi_{dr} = L_r i_{dr} + L_m i_{ds} \qquad \textbf{(8)}$$

$$\Phi_{qr} = L_r i_{qr} + L_m i_{qs} \qquad \textbf{(9)}$$

Where, V_{ds}, V_{qs}, are the d- and q-axis stator voltage, Φ_{ds}, Φ_{qs}, Φ_{dr}, Φ_{qr} are the d- and q-axis stator and rotor winding flux, i_{ds}, i_{qs}, are d- and q-axis stator current, i_{qr} and i_{dr} are d- and q-axis rotor currents (A) respectively, L_s and L_r are the stator leakage and rotor self-inductances (H), and V_s is the magnitude of the stator phase voltage (V).

The d-q steady state equivalent circuit of the DFIG is shown in Figure 3 below [52]:

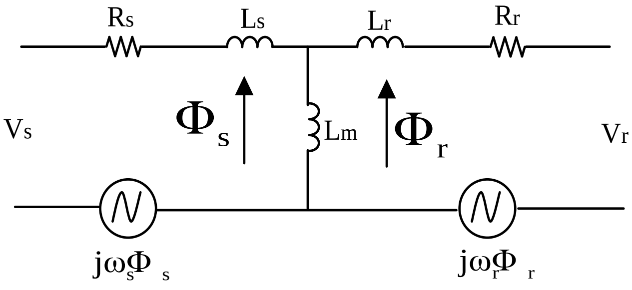

Figure 3: Equivalent Circuit of DFIG in Synchronous References Frame.

For independent control of active and reactive power output of the DFIG, vector control is normally used. This control techniques has many advantages compared to other strategies because it makes the control algorithm simple, robust and provides fast response.

For the rotor side converter (RSC) algorithm, it is assumed that the DFIG is connected to the power grid in which the grid voltage and frequency are constant. Fixing the d-axis of the synchronous frame on the stator voltage vector, a stator voltage oriented control is obtained. The vector of the stator voltage then becomes:

$$\bar{V}_s = V_{ds} + j\,0 \qquad \textbf{(10)}$$

According to (10), the active power and reactive power output from the stator side of the DFIG can be represented as:

$$P_s = V_{ds} i_{ds} \qquad \textbf{(11)}$$

$$Q_s = -V_{ds} i_{qs} \qquad \textbf{(12)}$$

Putting Equation (2) into (11) and (3) into (12) respectively, the active and reactive powers can be derived as follows:

$$P_s = \frac{V_{ds}(\Phi_{ds} - L_m i_{dr})}{L_s} \qquad \textbf{(13)}$$

$$Q_s = -\frac{V_{ds}(\Phi_{qs} - L_m i_{qr})}{L_s} \qquad \textbf{(14)}$$

From Equations (13) and (14), the active and reactive powers of the DFIG system are related to the rotor currents i_{dr} and i_{qr}, respectively. Therefore, the active and reactive power can be controlled via i_{dr} and i_{qr}, respectively, which is possible through the control of V_{dr} and V_{qr}.

Figure 4 shows the grid side converter (GSC) pulse width modulator rectifier. The aim of the control system is to maintain the DC-bus voltage to the required level for the RSC, while the main input currents should be sinusoidal and in phase with their counterpart voltages, for which the control system of DFIG maintains unity power factor condition.

For modeling and control design, the d-q synchronous frame voltage components are [48]:

$$V_d = e_d + L_{rec}\frac{d}{dt}i_d + R_{rec}i_d - \omega_s L_{rec} i_q \qquad \textbf{(15)}$$

$$V_q = e_q + L_{rec}\frac{d}{dt}i_q + R_{rec}i_q + \omega_s L_{rec} i_d \qquad \textbf{(16)}$$

Where R_{rec} and L_{rec} are resistance and inductance of boost inductor, respectively.

This strategy leads to getting the following active and reactive powers:

$$P_{rec} = V_d i_d \qquad \textbf{(17)}$$

$$Q_{rec} = -V_d i_q \qquad \textbf{(18)}$$

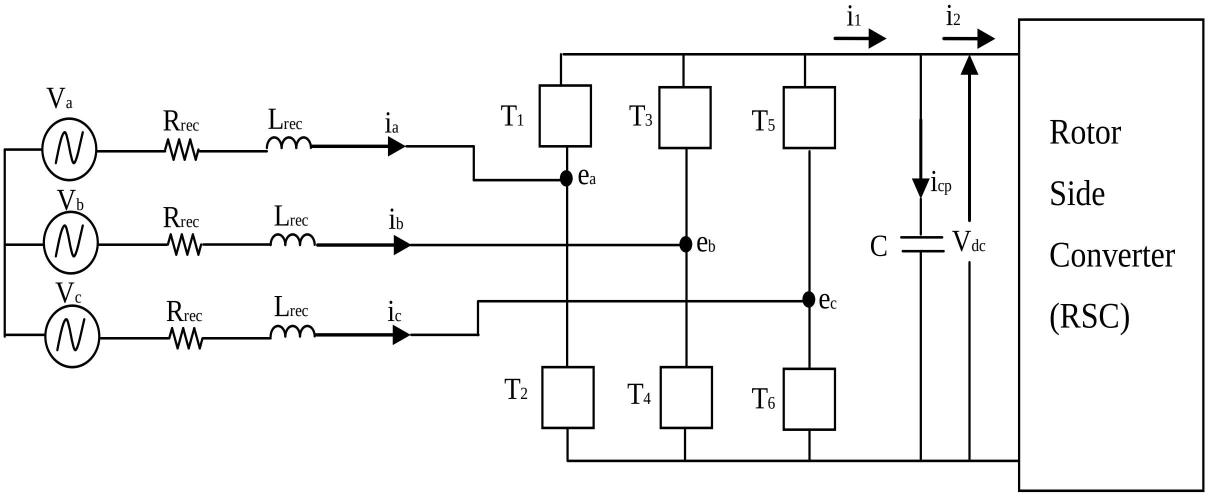

Figure 4: Structure of the Grid Side Converter of DFIG.

Thus, the current command q-axis controls the reactive power, whereas a current command of d-axis controls the active power, and consequently controls indirectly the DC-link voltage.

The above mathematical differential equation algorithms for the rotor side converter and the grid side converter, would now be applied to the VSWT in order to achieve the independent controllability of active and reactive power of the system.

Simulation Results and Discussion

Considering the prototype model presented in Figure 2, some of the system responses are presented in Figures 5-15.

In the simulation analysis, real wind speed data obtained in Hokkaido Island, Japan as shown in Figure 5 are used for the fixed speed wind turbine and the variable speed wind turbine in sections C and D respectively of the prototype model.

The simulation was run for 612 sec with a simulation timing step of 0.000001 sec to demonstrate the effectiveness of the controllers of the system.

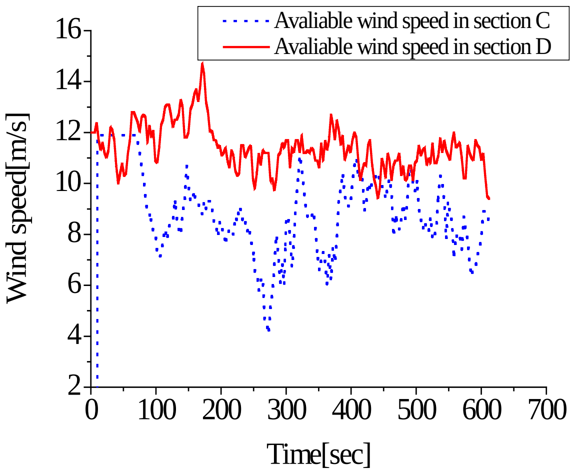

Figure 5: Available Wind Speeds for FSWT and VSWT Systems.

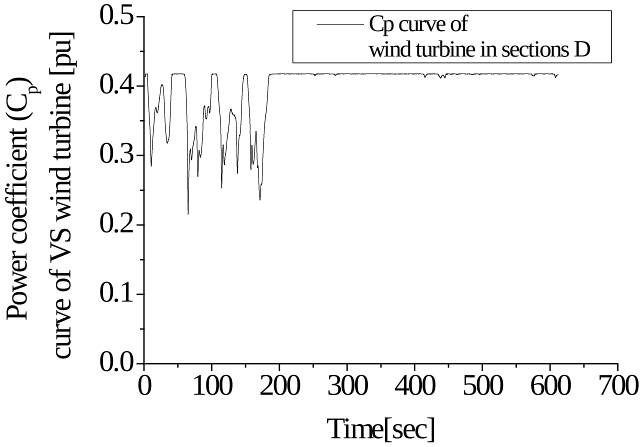

Figure 6: Power Coefficient Curve of VSWT.

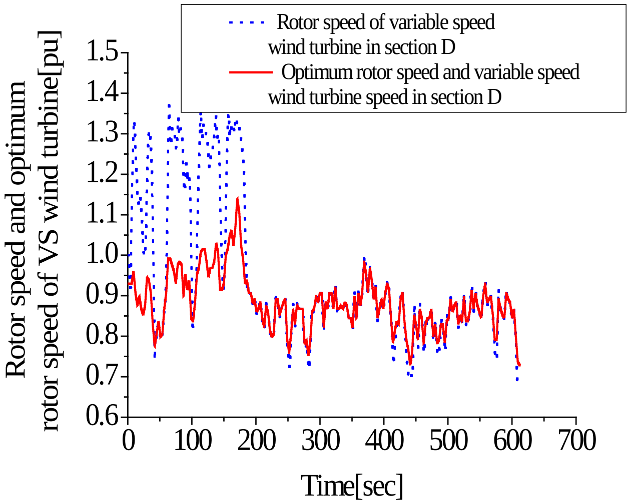

Figure 7: Rotor and Optimum Rotor Speed of VSWT.

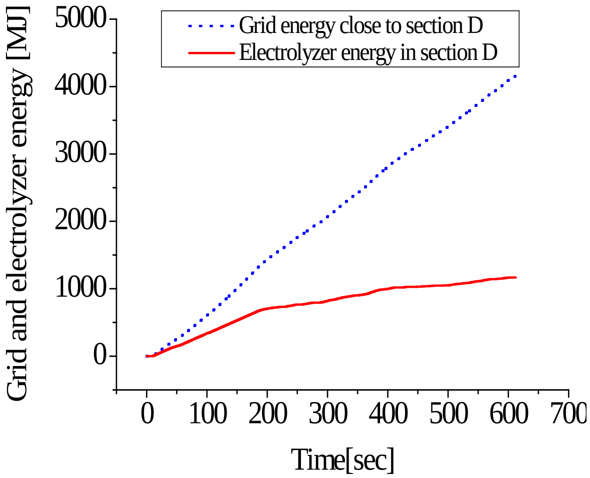

Figure 8: Energy of Grid and Electrolyzer Systems.

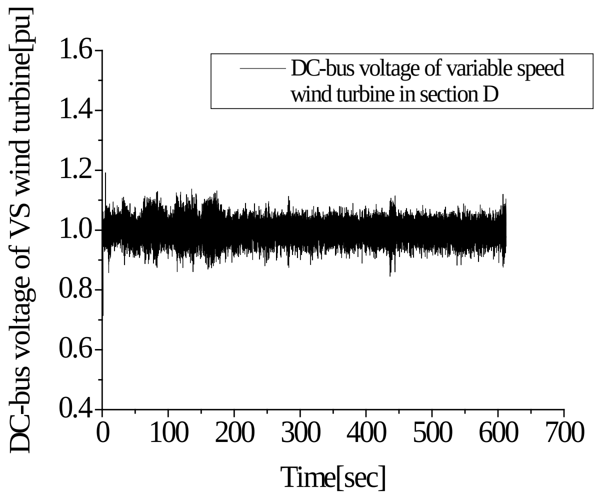

Figure 9: DC-Bus Voltage of VSWT.

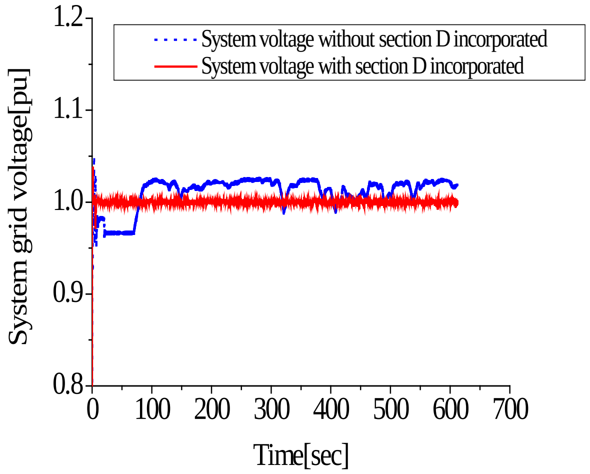

Figure 10: System Grid Voltages.

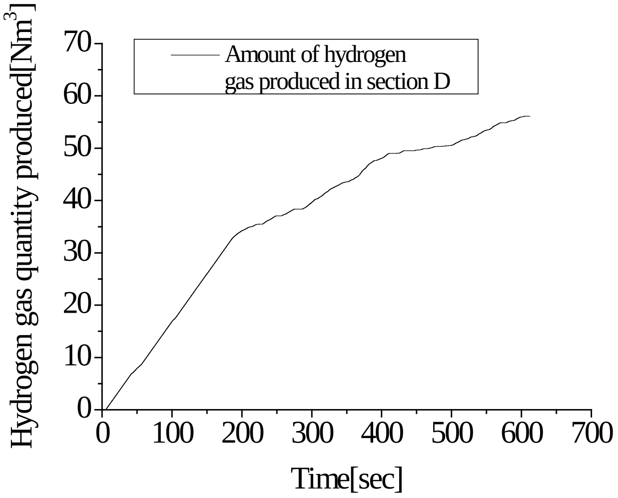

Figure 11: Amount of Hydrogen Gas Generated from the System.

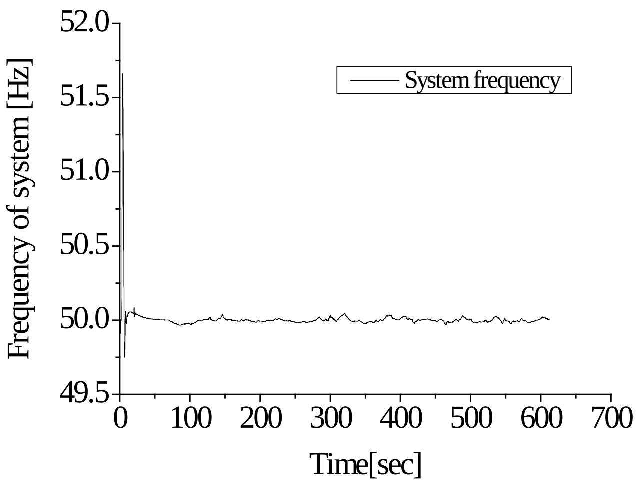

Figure 12: Frequency of the Network System.

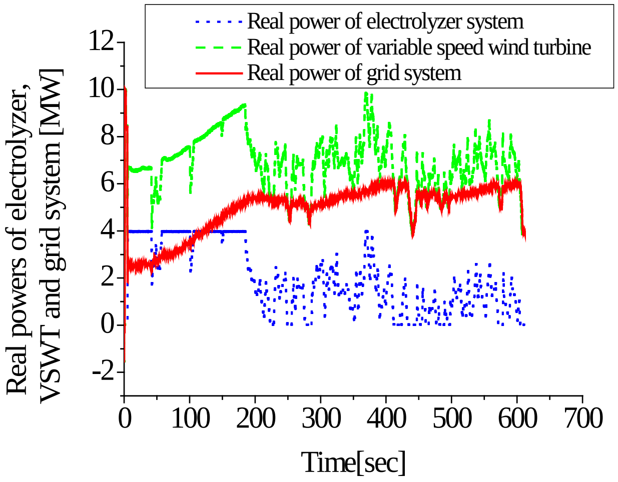

Figure 13: Real Powers of Electrolyzer, VSWT and Grid System.

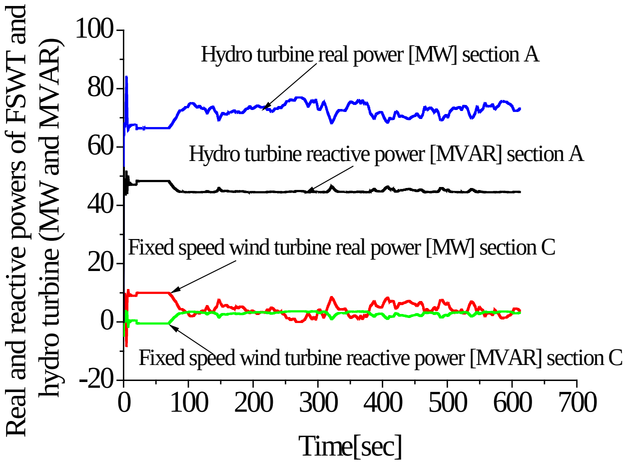

Figure 14: Real and Reactive Powers of FSWT and Hydro Turbine.

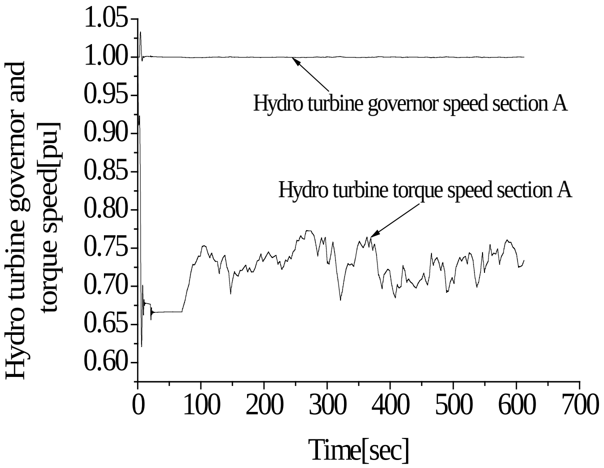

Figure 15: Hydro Turbine Governor and Torque Speeds.

The power coefficient response of the VSWT is shown in Figure 6 during the wind speed change of the VSWT, while Figure 7 shows the rotor and the optimum rotor speed of the VSWT. It could be observed from Figure 7 that the rotor speed of the VSWT follows the optimum rotor speed of the VSWT, demonstrating the effectiveness of the controller system employed. Consequently, maximum and wide range of power can be captured since the VSWT utilizes variable speed operation, making it possible to achieve a high efficiency of energy conversion compared to constant speed operation especially when the wind speed goes below the cut-out wind speed designed for the wind turbine.

Figure 8 shows the grid energy and the electrolyzer energy in MW for the system. As expected, the grid energy is higher than the electrolyzer energy. In Figure 9, the DC bus voltage was maintained effectively at 1.0 p.u, based on the control strategy of the VSWT system, despite the stochastic nature of the wind speed in Figure 5 for the VSWT system. At the same time, the grid voltage of the system was maintained constant at 1.0 pu, with section D connected to the network system. However, if section D is isolated from the network, the grid voltage of the network system cannot be maintained at 1.0 pu, rather, it follows the nature of the wind speed. This is due to the fact that there is no reactive power compensation device, which can help stabilize the grid voltage of the network system. Consequently, since the presence of the VSWT system in section D can help maintain the system grid voltage, the out of the wind generator that is connected to the electrolyzer system in section D is also smoothed. Therefore, hydrogen gas could be produced in section D as shown in Figure 11. The amount of hydrogen gas produced in Nm^3 gradually increases with time.

As discussed earlier, the diesel plant and other synchronous machines can control the system voltage and frequency to some extent, when the amount of wind speed is not much. The system frequency is shown in Figure 12. Since there is no flexible AC transmission system (FACTS) device like the super magnetic energy storage system (SMES) or the energy capacitor system (ECS) to contribute to the active power control, the system frequency cannot be controlled ordinarily. This is because, the conventional controller of the VSWT in section D and the FSWT in section C, does not have the capability for frequency control. However, if a flywheel adjustable control strategy is incorporated in the VSWT system in section D, the system frequency can be maintained, while at the same time smoothing the output of the wind generator in order to contain the high and low wind speed fluctuations.

The responses of the real powers of the electrolyzer, VSWT and the grid system are shown in Figure 13 for the dynamic analysis. The real and reactive powers of the FSWT and the hydro turbine in sections C and A respectively of the model system are shown in Figure 14. The hydro turbine governor and torque speeds in section A of the model system are shown in Figure 15.

CONCLUSION

A prototype model of grid connected multi-machines in a power system has been studied. Two wind farms were connected to the multi-machine power system. The first wind farm is made of only fixed speed wind turbines (FSWTs) and is onshore based. Variable speed wind turbines (VSWTs) exist in the second wind farm that is offshore based. An electrolyzer unit was connected to the smoothed terminal of the VSWTs system. It was found that the system grid voltage could be maintained effectively despite the stochastic nature of the available wind in the wind farms, with the help of the VSWTs. Another salient part of the study that was also reported is the production of hydrogen gas from the electrolyzer unit that is connected to the smoothed output of the VSWT system.

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