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Thermal Loading and Reliability Analysis for the Power Semiconductor in Wind Power Converter

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ABSTRACT*:* As a key component in the wind turbine system, the power electronic converter and its power semiconductors suffer from complicated power loadings related to environment, and are proven to have high failure rates. The steady growth of installed wind power together with the up scaling of the single wind turbine power capability has pushed the research and development of power converters toward full-scale power conversion, lowered cost per kW, increased power density, and also the need for higher reliability. A relative more advanced approach is proposed here, which is based on the loading and strength analysis of devices and takes into account different time constants of the thermal behaviors in power converter. With the established methods for loading and lifetime estimation for power semiconductor devices, more detailed information of the lifetime-related performance in wind power converter can be obtained.

KEYWORDS: power semiconductor device, thermal cycling, wind power converter, lifetime estimation.

1. INTRODUCTION

The fast growth in the total installation and individual capacity makes the failures of wind turbines more critical for the power system stability and also more costly to repair. Wind turbine system (WTS) technology is still the most promising renewable energy technology. It started in the 1980s with a few tens of kW power production per unit. Today multi-MW size wind turbines are being installed and they are very advanced power generators. There is a widespread use of WTSs in the distribution networks as well as there are more and more wind power stations which are connected to the transmission networks. Denmark for example has a high-power capacity penetration (> 30%) of wind energy in major areas of the country, and today 25% of all the electrical energy consumption is covered by wind energy. The aim is to achieve a 100% no fossil- based power generation system in 2050. Initially, wind power did not have any serious impact on the power system control, but now due to its size, wind power has to play a much more active part in grid operation and control.

The technology used in wind turbines was originally based on a squirrel-cage induction generator connected directly to the grid. Power pulsations in the wind were almost directly transferred to the electrical grid by using this technology as the speed is fixed (limited slip range). Power electronic converters are constructed by semiconductor devices, driving, protection, and control circuits to perform voltage magnitude and frequency conversion and control. A converter, depending on the topology and application, may allow both directions of power flow. There are two different types of converter systems: grid commutated and self-commutated converter systems. The grid commutated converters are mainly thyristor converters with high power capacity of 6 or 12 or even more pulses.

A thyristor converter consumes inductive reactive power and it is not able to control the reactive power. Thyristor converters are mainly used for very high voltage and power applications, such as conventional HVDC systems. The failure mechanisms of the power electronics are complicated and are affected by many factors. It has been revealed that the thermal cycling is the one of the most critical failure causes in power electronics system. The thermal behaviors of power electronic components can be generally classified into three time constants: long term, medium term, and short term. In a traditional wind power converter design process, the power switching device ratings are normally decided based on the potential current/voltage stresses, and some rating margins may be reserved to ensure certain reliability requirements. However, it is found that the loading distribution of power devices may be quite unequal under various converter topologies as well as operation conditions. With this traditional "rating-oriented" design process, it may easily lead to capacity waste of some less loaded devices. Therefore, more advanced models for wind power converter design are needed in order to satisfy the growing reliability requirements together with the most cost-effective solutions.

II. LIFETIME ESTIMATION OF WIND TURBINE

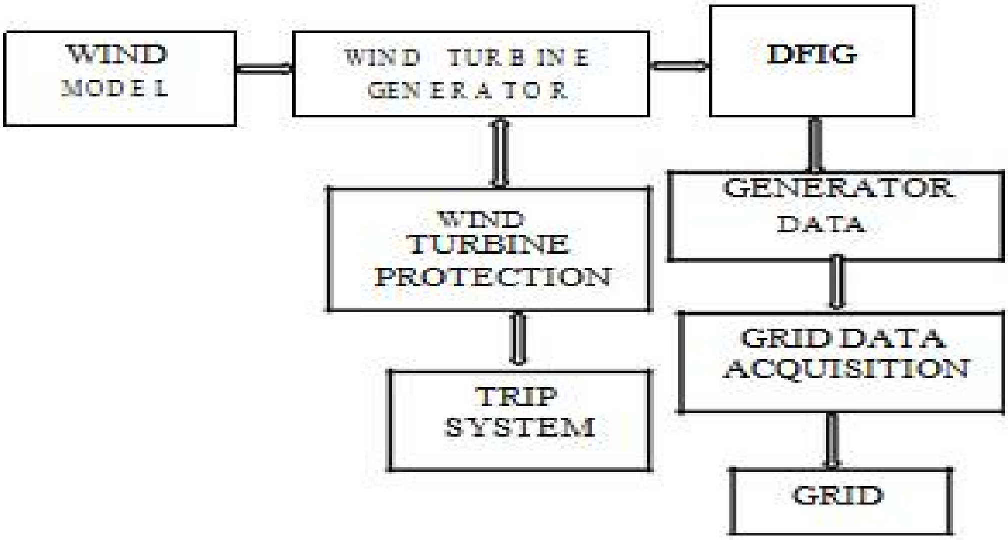


Fig 2. Life time estimation of wind turbine

The doubly-fed induction generator (DFIG) is widely used in variable speed wind energy conversion systems (WECS). This paper presents a review on various topologies, configuration, power converters and control schemes used with the operation of the DFIG. The Doubly-Fed Induction Generator (DFIG) is an induction generator with both stator and rotor windings. The DFIG is nowadays widely used in variable-speed wind energy applications with a static converter connected between the stator and rotor. As illustrated in Fig 2.

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

A wind turbine is a device that converts kinetic energy from the wind into electrical power. The term appears to have migrated from parallel hydroelectric technology (rotary propeller). The technical description for this type of machine is an aero foil-powered generator. The result of over a millennium of windmill development and modern engineering, today's wind turbines are manufactured in a wide range of vertical and horizontal axis types. The smallest turbines are used for applications such as battery charging for auxiliary power for boats or caravans or to power traffic warning signs. Slightly larger turbines can be used for making contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Arrays of large turbines, known as wind farms, are becoming an increasingly important source of renewable energy and are used by many countries as part of a strategy to reduce their reliance on fossil. For the DFIG, although it requires a power converter of only 25% of the generator rating in a speed range of 0.75–1.25 p u., the slip rings and brush arrangement on the rotor side increases the maintenance cost, and for the HVDC transmission, a voltage–source converter or a line-commutated converter has to be added because the output of the DFIG is three-phase constant frequency ac electricity. Wind turbines are available in a variety of sizes, and therefore power ratings.

The largest machine has blades that span more than the length of a football field, stands 20 building stories high, and produces enough electricity to power 1,400 homes. A small home-sized wind machine has rotors between 8 and 25 feet in diameter and stands upwards of 30 feet and can supply the power needs of an all-electric home or small business. Utility-scale turbines range in size from 50 to 750 kilowatts. Single small turbines, below 50 kilowatts, are used for homes, telecommunications dishes, or water pumping.

III. POSSIBILITIES AND LIMITS OF THE PROPOSED METHOD FOR LIFE TIME ESTIMATION

By the proposed life time estimation approach for wind power converter, some other interesting information related to the reliability of power devices can be acquired. The weak point which causes the reliability problem of the given wind power converter can be thereby discovered base plate and chip soldering fatigues caused by medium term thermal cycles. Because different lifetime models are used.

A more advanced approach for thermal profile mapping as well as lifetime estimation of wind power converter is proposed. It is based on the failure mechanism of power semiconductor devices, i.e., thermal stress generation and lifetime models, and a more complete mission profile of wind power converter are processed considering different time constants. It is based on the loading and strength analysis of devices and takes into account different time constants of the thermal analysis in power converter. In the wind power converter the thermal loading of the power devices does not periodically repeat but randomly changes with the wind speeds and ambient temperature. In the end some possibilities as well as limits of the proposed methods are discussed, and some experimental validations regarding the thermal loading of the power devices are given.

Wind turbines operate on a simple principle. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator to create electricity. Wind is a clean, free, and readily available renewable energy source. Every day around the world, wind turbines are capturing the wind’s power and converting it to electricity. With over 25,000 wind turbines installed globally, GE is one of the world's leading turbine suppliers. A wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity.

Wind is a form of solar energy and is a result of the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and the rotation of the earth. Wind flow patterns and speeds vary greatly across the United States and are modified by bodies of water, vegetation, and differences in terrain. Humans use this wind flow, or motion energy, for many purposes: sailing, flying a kite, and even generating electricity. The terms wind energy or wind power describes the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity.

IV. THERMAL TEMPERATURE ANALYSIS

Thermal analysis is a branch of materials science where the properties of materials are studied as they change with temperature. Simultaneous Thermal Analysis (STA) generally refers to the simultaneous application of Thermo gravimetric (TGA) and differential scanning calorimetric (DSC) to one and the same sample in a single instrument. The test conditions are perfectly identical for the TGA and DSC signals (same atmosphere, gas flow rate, vapor pressure of the sample, heating rate, thermal contact to the sample crucible and sensor, radiation effect, etc.). The information gathered can even be enhanced by coupling the STA instrument to an Evolved Gas Analyzer (EGA) like Fourier transform infrared spectroscopy (FTIR) or mass spectrometry (MS).

In addition to controlling the temperature of the sample, it is also important to control its environment (e.g. atmosphere). Measurements may be carried out in air or under an inert gas (e.g. nitrogen or helium). Reducing or reactive atmospheres have also been used and measurements are even carried out with the sample surrounded by water or other liquids. Inverse gas chromatography is a technique which studies the interaction of gases and vapors with a surface - measurements are often made at different temperatures so that these experiments can be considered to come under the auspices of Thermal Analysis. The basic principles of thermal analysis are similar to those in the electrical domain. Understanding one domain simplifies the task of becoming proficient in the other. This is especially clear when we consider thermal conduction .To reduce product development cost and time, traditional prototyping and testing has largely been replaced in the last decade by a simulation-driven design process. Such a process, which reduces the need for expensive and time-consuming physical prototypes, allows engineers to successfully predict product performance with easy to-modify computer models.

Design verification tools are considered invaluable in studying such structural problems as deflections, deformations, stresses, or natural frequencies. However, the structural performance of new products is only one of many challenges facing design engineers. Other common problems are thermally related, including overheating, the lack of dimensional stability, excessive thermal stresses, and other challenges related to heat flow and the thermal characteristics of their products.

V. THERMAL PROFILE GENERATION OF POWER DEVICES

It can be seen that multidisciplinary models like the wind turbine, generator, converter, as well as loss and thermal characteristics of the power devices are all included in order to map the mission profile of the wind turbines into the thermal loading of power semiconductors. Because the wind speed is sampled at 3 h and only long-term thermal behaviors are focused, the inertia effects of the wind turbine and generator which normally range in the time constant of seconds to minutes can be ignored. The output power of wind turbine can be looked up from the power curve provided by the manufacturer and can be directly used as the delivered power of converter.

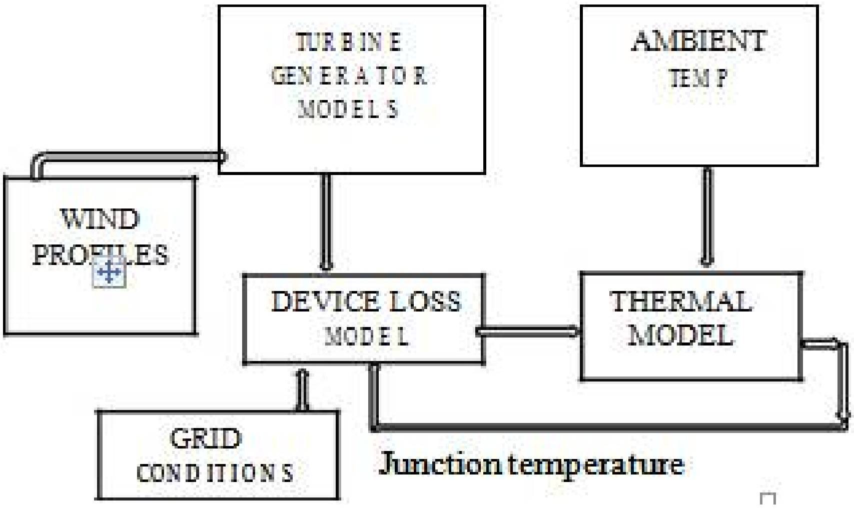


Fig 3. Multidomain models used for thermal profile generation of power devices

This group of thermal behaviors in the power devices is mainly caused by the fast and periodical current alternating in the converter. The junction temperature of power devices swings at relative smaller amplitude and at fundamental frequency of the converter output. Therefore, the generation of short- term loading profile can be significantly accelerated because the detailed circuit models with the switching behaviors can be avoided, and only analytical functions of as well as a series of simulations with medium time step are needed. There are many different approaches for lifetime modeling of power semiconductor devices, but they are not concluded yet and updated regularly.

Generally, the lifetime models provided by device manufacturers are more frequently used.

VI. SIMULATION

The detailed model includes detailed representation of power electronic IGBT converters. In order to achieve an acceptable accuracy with the 1620 Hz and 2700 Hz switching frequencies used in this example, the model must be discretized at a relatively small time step (5 microseconds). This model is well suited for observing harmonics and

control system dynamic performance over relatively short periods of times (typically hundreds of milliseconds to one second). A 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder.

Wind turbines using a doubly-fed induction generator (DFIG) consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. In this example the wind speed is maintained constant at 15 m/s. The control system uses a torque controller in order to maintain the speed at 1.2 per unit. The reactive power produced by the wind turbine is regulated at 0 Mar.

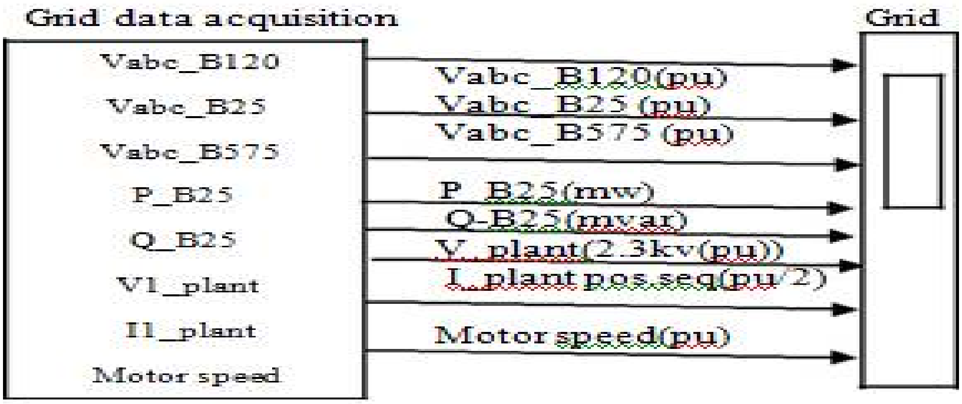


Fig 4 grid data acquisition Simulation diagram

The sample time used to discretize the model (T s= 50 microseconds) is specified in the Initialization function of the Model Properties. The turbine power, the tip speed ratio lambda and the values are displayed in Figure 2 as function of wind speed. For a wind speed of 15 m/s, the turbine output power is 1 per unit of its rated power, the pitch angle is 8.7 degree and the generator speed is 1.2 per unit.

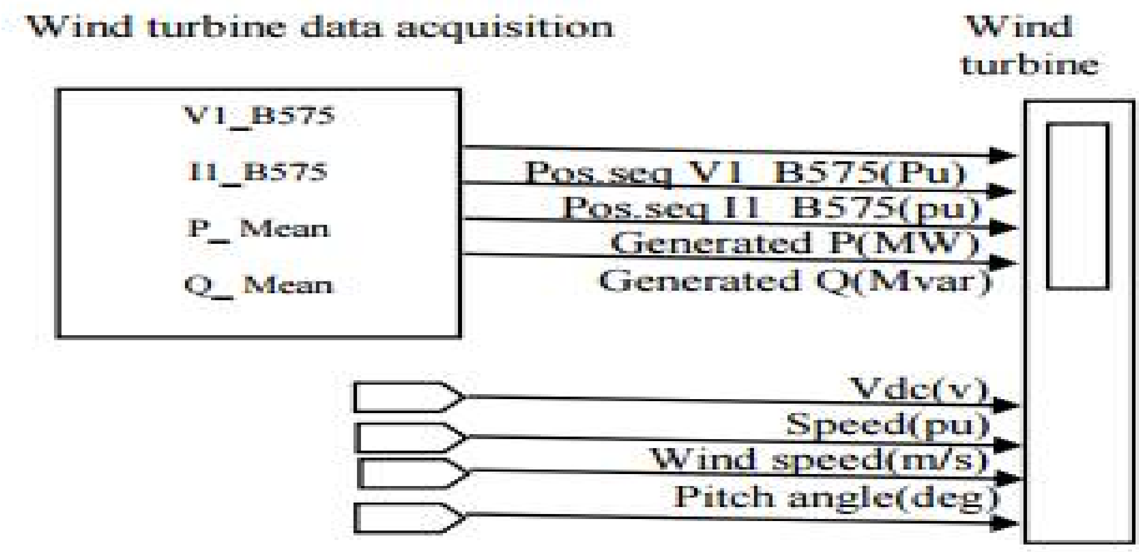
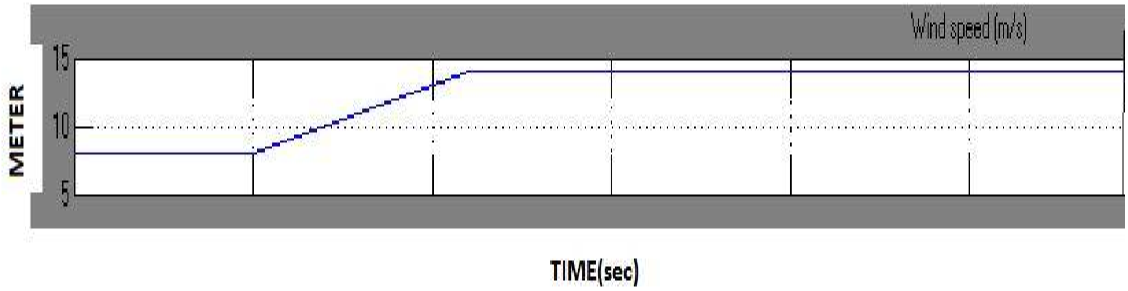
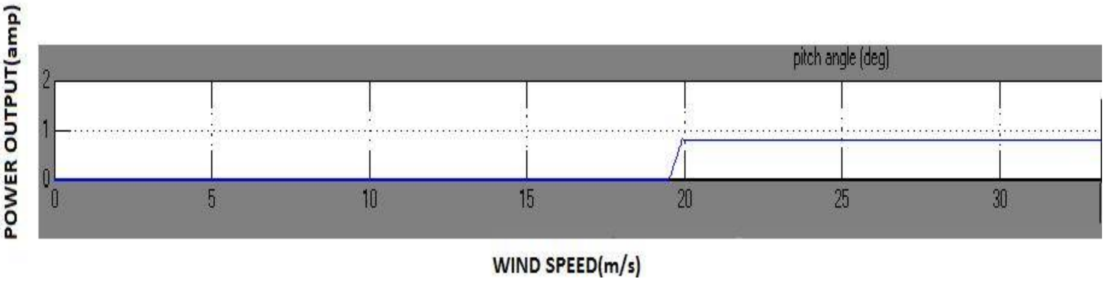


Fig 5 wind turbine data acquisition

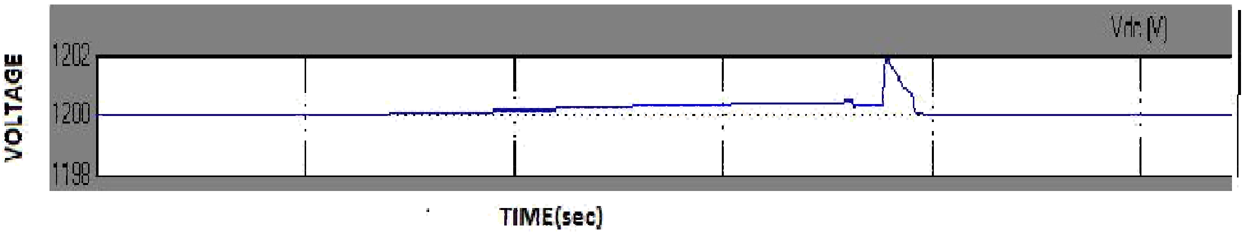
OUTPUT VOLTAGE FROM WIND TURBINE WIND SPEED

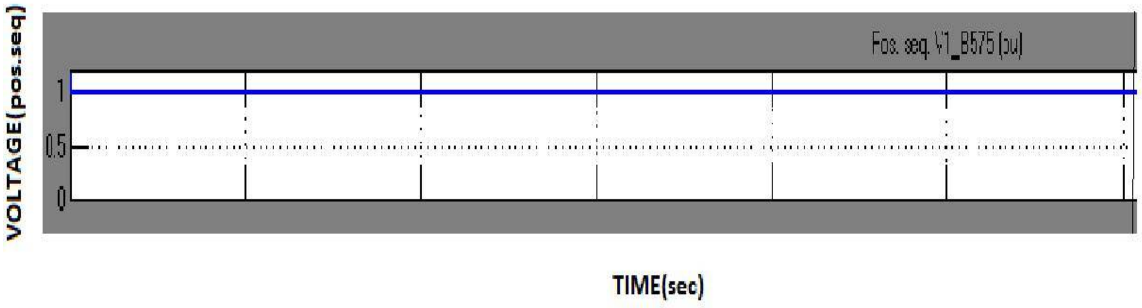


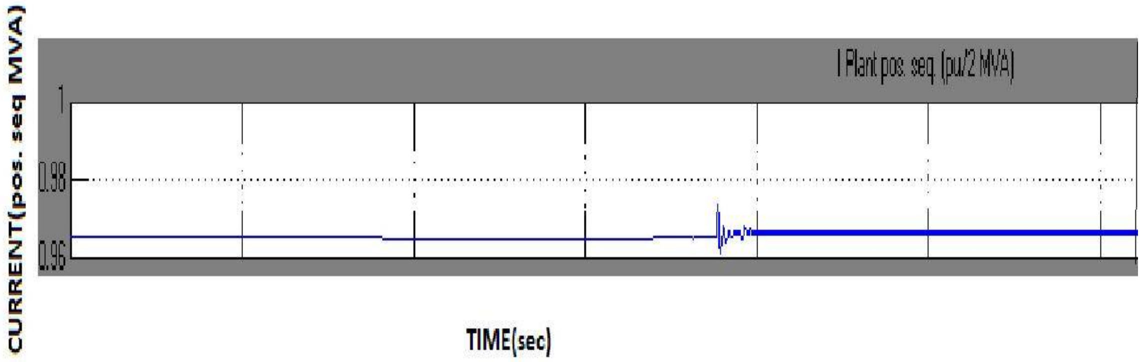
PITCH ANGLE



VOLTAGE POSITIVE SEQUENCE

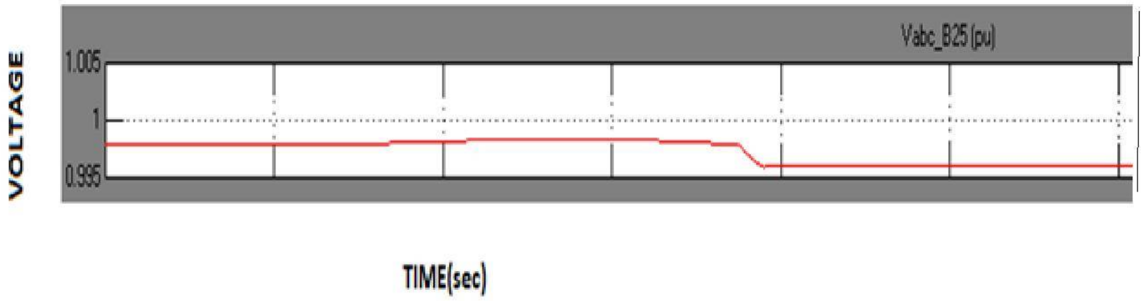


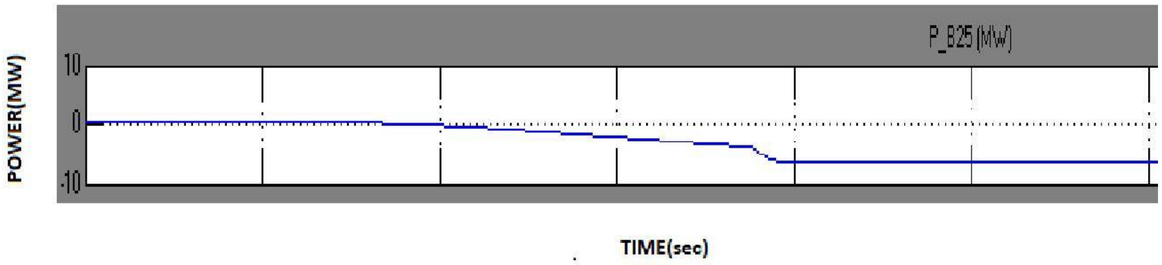




REACTIVE POWER IN GRID

RID VOLTAGE





ACTIVE POWER IN GRID

GRID VOLTAGE POSITIVE SEQUENCE

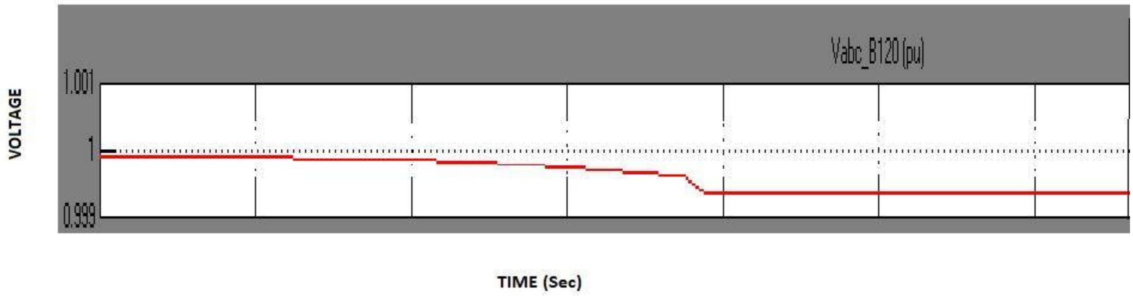


Fig 6 simulation output waveform

The doubly-fed induction generator (DFIG) system is a popular system in which the power electronic interface controls the rotor currents to achieve the variable speed necessary for maximum energy capture in variable winds. Because the power electronics only process the rotor power, typically less than 25% of the overall output power, the DFIG offers the advantages of speed control with reduced cost and power losses. This PLECS demo model demonstrates a grid-connected wind turbine system using all of PLECS' physical modeling domains. The system model includes a mechanical model of the blades, hub, and shaft, a back-to-back converter including thermal loss calculations, a magnetic model of the three-phase transformer, and the transmission line and grid.

A 9-MW wind farm consisting of six 1.5 MW wind turbines connected to a 25-kV distribution system exports power to a 120-kV grid through a 30-km, 25-kV feeder. A 2300V, 2-MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 PF) and of a 200-kW resistive load is connected on the same feeder at bus B25. Both the wind turbine and the motor load have a protection system monitoring voltage, current and machine speed. The DC link voltage of the DFIG is also monitored.

VII. CONCLUSION

This paper has reviewed the power electronic applications for wind energy systems. Various wind turbine systems with different generators and power electronic converters are described. Different types of wind turbine systems have quite different performances and controllability. The electrical topologies of wind farms with different wind turbines are briefed.

It has been shown that the wind farms consisting of different turbines may need different configurations for the best use of the technical merits. Furthermore, the possible methods of improving wind turbine performance in power systems to meet the main grid connection requirements have been discussed. With the established approaches for loading profile generation and lifetime estimation, more possibilities and details of the lifetime information for wind power converter can be obtained like the lifetime consumption by different thermal behaviors, wind speeds, and failure mechanisms. This is very useful to indicate and improve the weakness of the system in respect to the reliability performance. The estimated thermal behaviors in the power devices are validated on a downscale experimental setup.

It is also found that in the wind power application, many loading conditions of power devices that are not covered by most of the lifetime models by manufactures could be presented. Therefore, more advanced lifetime modeling and power cycling tests are required for the lifetime estimation of converter.

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