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Mechanical Design of a 750 ㎾ Direct-drive Wind Turbine Generator System

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***Key Words** : KBP-750D, Direct-drive, Drive train, Loads*

ABSTRACT

A prototype of 750 ㎾ direct-drive wind turbine generator system, KBP-750D is under development in Korea. For the gearless, direct-drive prototype a synchronous generator with permanent magnets has been developed. The upwind 3-blade type machine employs variable speed and pitch control. The operating ranges of wind and rotor speed are 3 to 25 m/s and 9 to 25 rpm, respectively. The tip speed ratio of rotor blade is 7.5, designed for power coefficient 0.47. The blade pitch and torque are controlled with the predefined torque-speed curve according to the conditions of wind and public electric grid. This paper describes the outlines of primary components of KBP-750D.

1. Introduction

The wind turbine generator system (WTGS) the Model KBP-750D with advanced features of direct-drive, variable speed and pitch control is a first gearless type WTGS of medium scale, developed in Korea. The detail descriptions for the characteristics and primary components of KBP-750D are introduced in the next following sections.

2. Characteristics of KBP-750D

The WTGS, which is under development and called "Model KBP-750D", is a gearless, direct-drive type. It is designed to fulfill the requirements for theIEC Type Class 1A in account that Korea is on the route of typhoon developed in the South Pacific Ocean. The rated power 750 kW is reached at the rated windspeed of 12 m/s and rotational speed of generator, 25 rpm. The cut in and out wind speeds is 3 m/s and 25 m/s, respectively. The tip speed ratio (TSR) of rotor blade is selected 7.5 for the power coefficient 0.47. In partial load conditions, the torque is controlled by a predefined torque-speed curve to extract maximum wind energy with maintaining the design TSR of the rotor. Above the rated speed, the power is controlled by blade pitch control and torque control simultaneously to obtain the rated power within 10% of error.

The drive train is a key feature in the design of WTGS. More than 10 concepts of drive train adopted in existing turbines and devised in concept studies were assessed to derive our own system [1].With these assessments and consideration of technology trends a gearless, direct-drive power train is selected as shown in Fig. 1. The generator is powered directly from the 3-blade rotor through the shaft supported by two main bearings. To enhance the reliability of aerodynamic brake the independent blade pitch control in each blade is

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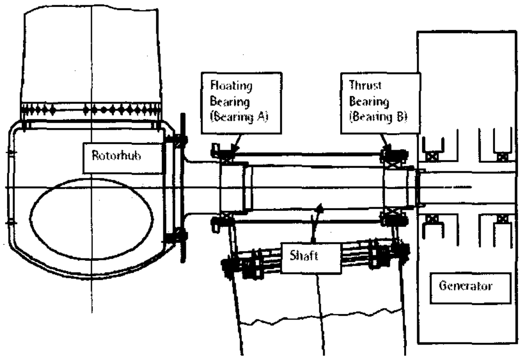

Fig. 1 Schematic drawing of drive-train, KBP-750D

chosen. The nacelle traces the wind directions with an active yawing system powered by 3 electric motors. The aerodynamic brake by pitch control and mechanical brake by hydraulic power are key elements for the safety and protection against the extreme wind conditions and critical operation faults. The blades are protected from lightning by its protection system attached at each blade tip.

The hub height is 50m and the diameter of blades is also 50m. The total weight of nacelle including blades, hub, generator, machine frame, and minor components is about 55 tons. Nacelle with spheroidal shape encloses all the subsystems and components, not to be exposed in environment directly. The design parameters of KBP-750D are summarized in Table 1. The primary components of KBP-750D are introduced in the next sections.

3. Load Calculation

Table 1 Design parameters for KBP-750D

Rated power	750 ㎾
Rated wind speed	12 ㎧
Range of wind speed	3~25 ㎧
Power control	Blade pitch
Tip speed ratio	7.5
Nominal rotor speed	25 rpm
Range of rotor speed	9~25 rpm
Rotor diameter	50.0 m
Hub height	50.0 m

A WTGS is exposed in very severe natural conditions such typhoon, snow, heavy fog, and etc and is suffered from a machine fault combined with those aggressive conditions. A WTGS must be designed with reflection that it is expected to experience all the normal and abnormal status of machine and environmental conditions during its service lifetime in order to assure safety and its performance. The sorting of load cases and calculation is complied mainly with the regulations of IEC 61400-1 and partly with the guidelines of Germanischer Lloyd. The load calculations of KBP-750D are based on IEC Type Class 1A. All 22 load cases are selected from DLC 1.1 (Design Load Case 1.1) to DLC 8.1 according to IEC 61400-1. They also have their own branches in combination with wind speed and direction (yaw error) and turbulent intensity. Depending on load cases the load is divided into the ultimate load and fatigue load. The latter is calculated only in conditions related to the normal operation and startup/stop. The ultimate loads with partial safety factors are picked out from raw data of calculations. The fatigue loads without reflection of safety factor are estimated with post statistical processes by using Weibull probability distribution.

The loads were calculated on blades, hub, main shaft, machine frame and tower for all load cases [2]. The loads on the blades and tower are computed on several positions based on design

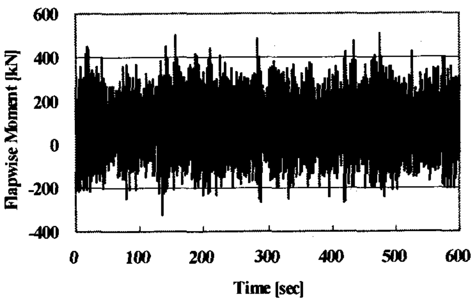

Fig. 2 Flap-wise moment on blade root in DLC1.2k1

practices. Some secondary loads such as pitch drive system, yaw system, and etc are inter-/extra-polated from the results of the positions calculated directly. All loads are computed with computer code "BLADED" [3]. As an example of load calculation, the flap-wise moment on blade root at mean wind speed 25m/s is shown in Fig. 2.

4. Drive train

KBP-750D is a variable speed, direct-drive wind turbine with radial flux, permanent magnets synchronous generator. It consists of fivemain parts such as rotor with blades and hub, main shaft, generator, machine frame and tower as shown Fig. 1. The machine frame supports main shaft connected with rotor blade through hub and generator. Because the shaft supported by two bearings is very long and transmits aerodynamic torque to generator directly and is subjected to large bending moment from the weights of rotor and generator at both ends, it is rather thick. The generator is connected to shaft with shrink disks. The torque of generator is also transmitted to the machine frame by torque arm. The generator is supported by shaft. Therefore, two torque arms at generator housing carries only torque. The details of subsystem are described below.

4.1 Main shaft

The main shaft with length of 3,376mm is a tapered rod with 100mm bore for the wire path of instruments. There are several steps (seats) for installation of bearings and generator on the main shaft as shown Fig 3, but they does not encroach its strength as proved from the FEM simulation [4]. The FEM analysis gave that the throat at hub side was the highest stressed region. This is due to bending loads from dynamic behaviors of rotor. The shaft was designed in taper with 526mm at hub side and 413mm at generator side. The shaft made of steel alloy, 42CrMo4-QT (DIN EN 1008 T1) is fabricated with ingot casting and forging.

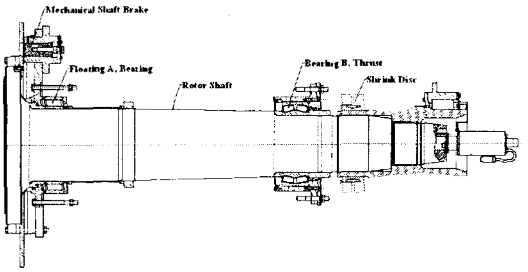

Fig. 3 Main shaft assembly

4.2 Main shaft bearing

Two rotor bearings connect the shaft with the machine frame. The bearing A (toroidal roller) only floats the rotor shaft without resistance against thrust, while the bearing B (spherical roller) not only floats but also support the shaft against its thrust as shown in Fig. 3. The lifetimes of bearing A and B due to dynamic loads, L10 (lifetime with 10% probability of failure) are 5,921,000 hours and 448,254 hours respectively. SKF [5] C39/530M and 24084 ECA/W33 are selected as bearing A and B from the static and dynamic load analysis.

4.3 Machine frame

Machine frame supports all subsystems except tower. Particularly, the yaw drive system is attached directly to the main frame. As shown in Fig. 4 the welding structure of machine frame is made up out of a cylindrical section with a

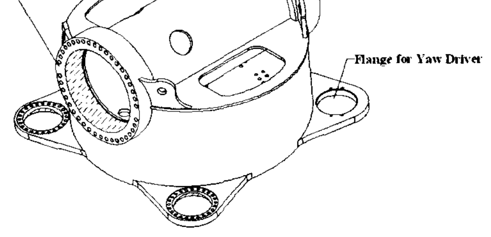

Fig. 4 Machine frame

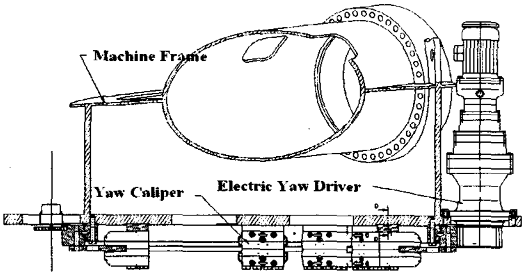

Fig. 5 Yaw drive system

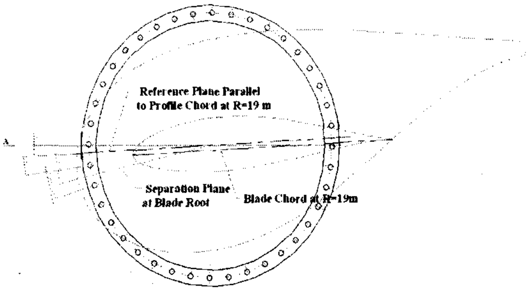

Fig. 6 Reference profiles of blade

horizontal bedplate and a skewed top plate. Two rings at cylindrical pocket for shaft act as support for the bearings of the main shaft. The high stress is concentrated near to welding region between two bearing pockets and vertical frame [6]. The extreme load on machine frame arises by torque due to emergency stop.

4.4 Yaw drive system

The KBP-750D is yawed when the operation control system detects a sufficiently large misalignment. Yawing is carried out with a yawing speed of 0.8°/sec referring to yaw bearing axis. The operations can be divided into equal numbers of clockwise and counter clockwise movements. When there is no yaw movement the nacelle is held by yaw brakes and the gearing is free of external loads. During yawing the brake torque decrease to app. 25% of hold torque. The remaining torque prevents the gearing from extreme peak loads. The yaw drive system consists of 3 electric motors with gear, 4 point-bearing with gearing tooth and 8 calipers as seen in Fig. 5.

5. Rotor

5.1 Blade

The rotor blade KBP-750D is designed for IEC type class 1. The blade geometry is designed on the basis of modified NACA 63x-xxx and AE02-xxx profiles. NACA63 series were selected due to their good performances. The profile of NACA63 is distributed in radial position from the blade root between 68% and 100%, in which the significant portion of aerodynamic force is produced. The circular profile is selected at blade root to connect with hub flange smoothly. The profile of AE02 series is distributed up to 68% of blade to secure the structural strength. They are thick but give a good aerodynamic performance.

The rotor blade is 24.25m long and is manufactured in prepreg laminates. The blade structure comprises biaxial sandwich shells with 4 main UD glass tape spar caps and a mixed staggered biaxial and UD glass build-up in the blade root to transfer loads into the blade connection. The blade consists of an upper (aerodynamic pressure side) and a lower (aerodynamic suction side). Shell with two spars consisting of two UD spar caps and one multi-axial sandwich spar web each as supporting structure. The spar caps are designed in UD glass/epoxy prepreg, the shells and the spar webs in biaxial glass/epoxy prepreg and the blade root reinforcement in a mixture of UD and biaxial glass/epoxy prepreg. Where the shell is not supported by the UD spar caps, it is built as sandwich structure with glass reinforced PUR foam. Upper shell, lower shell and the spar webs are manufactured in separate moulds. The shells are bonded at both the leading and trailing edge and to the spar webs, which connect the nose and tail UD spar caps of each shell half. The blade root is connect to the hub with a T-bolt connection. The details about the aerodynamic and structural designs can be referred in [7].

5.2 Rotor hub

The rotor hub is one of the most highly stressed components of WTGS. All rotor loads are concentrated here. The hub of KBP-750D is made of the nodular iron [GJS-400-18U-LT] by casting. After casting, the residual stresses were released to mitigate stresses from dynamic loads. As shown Fig. 7 the hub has 3 flanges for attachment of blades, 1 large flange for shaft, and one access hole. The stresses are concentrated around the flanges neck for blades [8].

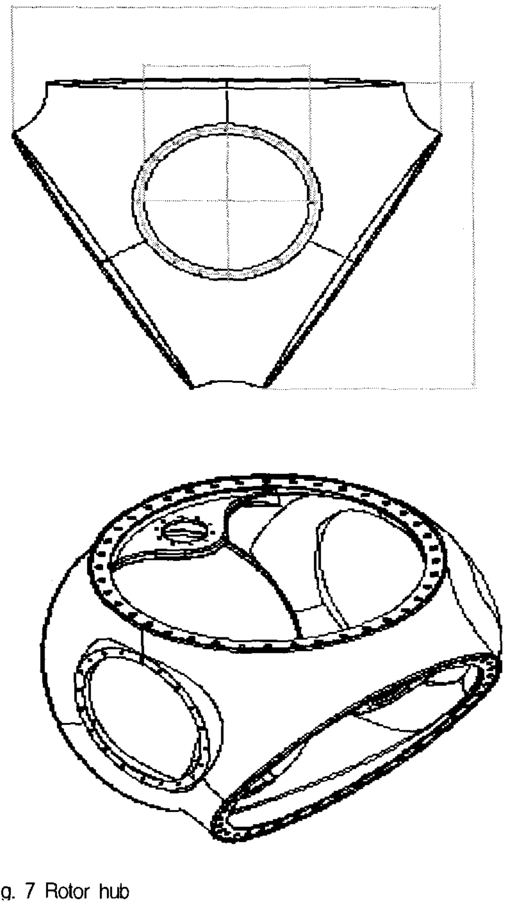

Fig. 7 Rotor hub

5.3 Pitch drive

The pitch drive of the three-blade rotor is used for power control and aerodynamic braking of the wind energy converter. The rotor blade is secured at its root to the rotor hub by means of a rotary joint with internal teeth. One pitch drive per rotor blade moves the blade to certain pitch positions according to the prevailing wind speed. Each rotor blade has its own pitch drive system. All the electrical components, including batteries and control electronics of the pitch system, are located in the hub and rotate at a shaft speed between 9 rpm and approx. 27 rpm. As a result, all the components are constantly exposed to centrifugal forces, and there are continuous changes of direction of the weight forces. In addition, inertia forces are felt because of rotational fluctuations and during power-up and power-down routines. During operation, the pitch ranges only from 0° to approx. 30° for power control at a wind speed of approx. 12m/s and higher. Here, the rotor speed is kept constant by the pitch and torque controls. The blade is turned 90° to vane position for shutdown of the wind energy converter. Fig. 8 shows the assembly of pitch drive assembly.

6. Generator

The generator is designed to have 42 pole pairs of permanent magnet at frequency of 7-17.5 Hz, which is enough for the efficient inverter operation. The magnets generate radial field to cross electric field perpendicularly. The electric capacity is 800 ㎾ with efficiency, 0.95. The dimension is 3.32 m 0.9 m long and its weight is about 20 tons. The air gap radius of the stator 1660 mm and its gap is 4.5 mm. The more detail of design is described in Ref. [9].

7. Electronic Power Converter and Control & Protection Systems

KBP-750D requires an electromechanical converter to grid the power from generator into the public electric network, with intervening between generator and grid network. The converter smoothes the fluctuation of power output by the torque control as well as controls the generator power according to the grid conditions. The converter consists of AC/DC/AC power converter, which is based on an IGBT, reactor and protection panel. The design specifications are as follows; rated grid voltage of 690 V with output frequency of 60 Hz, the maximum output current of 643 A, the rated DC link voltage of 1250 V, the inverter efficiency of over 94%.

A PI controller is used for the torque controller, in which torque is controlled via rotor speed to operate the turbine at the optimum condition which gives maximum efficiency. The more detail of power converter and control system are described in Ref. [10].

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