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A novel hybrid transmission for variable speed wind turbines

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ABSTRACT

We herein advance a novel, power summation hybrid transmission, which has the ability to convert the variable speed of a wind turbine rotor shaft into the constant speed required at a generator shaft for a whole range of wind speeds, thereby eliminating the need for a frequency converter. The transmission consists of a single one-stage planetary gear train (PGT) with three rotating shafts and a simple control system consisting of a few sensors and a control motor controlled by a microprocessor. One of the PGT shafts is the input, another is the output, and the third is coupled to the control motor as second input. The optimal tip-speed ratio is kept constant at low wind speeds by controlling the speed of the control motor, maximising the capture of energy from the wind. The wind-rotor speed continues to vary above the rated wind speed zone, but the rotor shaft power is kept constant by using the same control system. In this way, a constant electrical power output is achieved without altering the blade pitch, i.e., with the rotor in a fixed geometry. A frame design procedure for the transmission is proposed, efficiency expressions are derived, an example transmission operation is presented and efficiency comparisons to a mainstream variable speed wind turbine are carried out.

1. Introduction

Concerns over global environmental threats and energy crises have contributed to the increasing use of renewable energy technologies. The production of electrical power from wind is the fastest growing and most cost effective sustainable energy technology.

The objective of any system for utilising wind energy is to capture as much wind energy as possible at the lowest possible cost. There have been many attempts to achieve this using horizontal-axis wind turbines, which should deliver power at a constant frequency, whether they are connected to the grid or not. Many common appliances will not function properly if a constant frequency is not maintained [1]. Wind turbine rotors achieve their maximum efficiency at a particular tip-speed ratio. Therefore, stiff-grid-connected, constant-speed turbines, in which the wind rotor is connected to a generator at a fixed speed ratio, operate sub-optimally. Whilst such turbines require no frequency converter, any rapid changes in electrical output will either cause the generator to be damaged or cause the generator circuit breaker to open. The fatigue loads are also increased, resulting in a reduced lifetime of the system or in an increased size and cost of the gearbox. It is therefore necessary either to control the power output from the wind rotor or to find a way of transforming the varying voltage and frequency to make the generated power compatible with the electrical grid [2]. Variable speed wind turbines have recently been used, which have a constant optimal tip-speed ratio below the rated wind speed and a constant speed and power output above it [3]. This type of turbine has a number of advantages: i) below the rated wind speed, the speed of the wind rotor varies with the wind speed to maintain the maximum power efficiency (commonly by controlling the torque of the generator shaft); ii) control of the rotor torque significantly reduces variations in gearbox torque above the rated level; iii) low rotor speeds in slow winds result in significantly lower aerodynamically generated acoustic emission than that obtained from other turbines; iv) the rotor can operate as a flywheel, smoothing the torque variations caused by short-lived power fluctuations in the rotor that may be caused by varying wind conditions. The shortcomings of variable speed turbines are that they require frequency converters and complex control systems. Electrical harmonics are also a critical issue for these turbines because they distort the normally smooth sinusoidal voltage [2].

The solution to the problem of capturing the maximum amount of wind energy at the minimum production cost has become a key challenge for designers and scientists, and considerable efforts have

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been made to develop various transmissions [4–13]. In all of them, a variable speed wind turbine is used with a transmission that gives a constant output speed over the entire range of possible wind speeds and a constant power output in the most effective range of wind speeds. Here, we comment on some of the most successful, in our opinion, all hybrid types of continuously variable transmission (CVT) and all comprising at least one PGT. Other transmissions [10–13] are not considered here because of their relatively low efficiencies due to friction member (belting or traction drives).

Idan and Lior [4] proposed a hybrid variable speed transmission with two planetary transmission stages in which the annulus gear speed of the second stage (three rotating shafts) was controlled by three servo-motor generators (SMGs) to maintain the optimal rotor speed for a given wind speed, while the speed of the conventional asynchronous generator coupled with the sun gear was held constant. This design fulfils most of our requirements, but has some shortcomings, including a high cost for the electronics because of the three SMGs used to balance the radial forces, the fact that one fixed ratio PGT stage seems to be surplus, and that, when operated as a generator, the SMGs need a frequency converter to deliver power to the grid. Hicks and Cunliffe [5] presented a transmission consisting of a single PGT with its output shaft connected to the induction generator through a bevel gear drive, and the third shaft connected to a single SMG, which, assisted by the control system, made it possible to maintain the output shaft at a constant (±15%) speed. The shortcomings of this transmission are that the output speed is not quite constant, the bevel gear pair increases the transmission cost and power losses, and there are problems associated with the delivery of the SMG power to the grid. Zhao and Maiβer [6] designed a power-split transmission with an electronically controlled PGT and two adjustment gear pairs, with one of the PGT shafts connected to the rotor shaft over the gear pair, another coupled to the generator, and the third shaft connected to the SMG. The output generator speed was kept constant by controlling the speed of the servo motor. Apart from the questionable use of two additional gear drives, which increase the machine costs and power losses, the same problems arise when delivering the SMG power as previously described. In another scheme [7], a transmission has a single PGT, achieving a constant output speed by controlling the variable third shaft speed using a torque converter driven by the output shaft. Although this is an interesting, innovative solution, beside the transmission, there was a conventional gear drive which additionally increases the power losses and production costs.

Each of the transmissions considered above has problems associated with connecting the SMGs to the grid. Namely, an important question has not been addressed in those papers: are the SMGs connected to the same high voltage grid as main generator or to some other, low voltage grid? If the former is true, then the additional transformer is needed between SMGs and the grid. When the power of SMGs is delivered to the grid, the frequency converter is needed to be built in.

The recently developed independently controllable transmission is also capable of running the output shaft at controllable speed independent of the input speed, even without control system [8,9]. This promises to solve most of the problems associated with variable-speed transmissions including in wind turbines. The transmission consists of two PGTs with three rotating shafts connected by two gear drives. However, there is one surplus output shaft with a variable, uncontrollable speed. The problem remains of how to manage the power of this shaft.

We herein advance a simple, hybrid CVT that can convert the variable speed of a wind turbine rotor into a constant generator shaft speed over an entire range of wind speeds [14]. It has all of the advantages of a variable speed turbine, capturing the maximum wind energy in the low-wind-speed zone, and allowing a constant electrical frequency to be produced without using a frequency converter. The transmission consists of a single PGT controlled by a control system, which is also used to maintain a constant power from the wind rotor shaft at wind speeds greater than the rated.

2. General description of novel transmission system

The transmission system consists of a simple, power summation PGT, with a positive basic gear ratio and a control system. The transmission input shaft is connected to the wind turbine rotor; the second, hollow shaft is connected to the control motor; and the third, output shaft (passing through control motor shaft) is connected to the generator (Fig. 1).

The transmission input shaft (wind rotor shaft) is connected to the central gear 1 shaft of the PGT, the output shaft is connected to the central gear 3 shaft, and the planet carrier (later simply called the carrier) shaft is connected to the control motor shaft. Planets 2 and 2′ are in one piece with a shaft that is supported by the carrier C. The rotational speeds of the shafts of the three main PGT members, central gear 1, central gear 3 and the carrier (i.e., the speeds of the rotor, generator and control motor shafts n_R, n_G, and n_M, respectively) are related to the basic gear ratio i_0 of the PGT by the Willis equation [15,16]:

$$n_R - i_0 n_G + (i_0 - 1)n_M = 0, \tag{1}$$

where the basic gear ratio is defined as

$$i_0 = \frac{z_2 z_3}{z_1 z_2'} = \frac{n_1 - n_c}{n_3 - n_c} = \frac{n_R - n_M}{n_G - n_M}, \tag{2}$$

where z_1, z_2, z_3 and z_2' are the numbers of teeth on gears 1, 2, 3 and 2′, respectively, and n_1, n_3, and n_c are the rotational speeds of gears 1 and 3 and the carrier C, respectively.

The basic PGT gear ratio should not be chosen arbitrarily, and its constraints, as well as those on the speed ratio, must be determined for this type of transmission. First, the signs (+/−) of the speed and torque must be determined for each shaft. As usual, the input speed and torque are taken to be positive. Then, for a chosen positive basic gear ratio $0 < i_0 < 1$, from Eq. (4), the generator shaft torque becomes negative, as does the control motor shaft torque (from the torque equilibrium equation). Therefore, the rotor shaft is the (torque) summation shaft, and the generator shaft is the power summation shaft. Because the control motor shaft power is positive

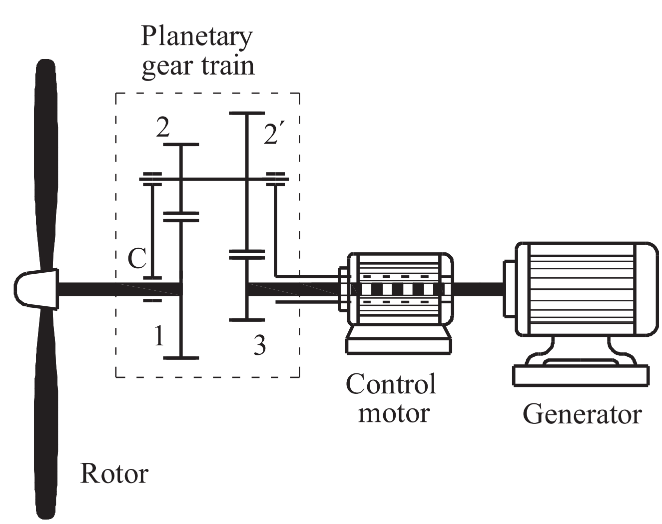

Fig. 1. Schematic of the proposed wind turbine drive-train.