Kinematic and Dynamic Analyses of A Series-Type Independently Controllable Transmission Mechanism

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Abstract – An innovative transmission mechanism, referred to as a series-type independently controllable transmission (ICT), is proposed in this study. The series-type ICT is an alternative form of the parallel-type mechanism proposed in the former researches and can produce a required angular output velocity that can be independently manipulated by a controller and does not depend on the angular velocity of the input shaft. While being applied to variable speed wind power systems, the ICT mechanism could overcome turbine speed fluctuations and provide constant speed input to the drive shaft of the generator to generate electricity with constant frequency. The series-type ICT is composed of two planetary gear trains and two sets of transmission-connecting members. Kinematic and dynamic characteristics of the series-type ICT are investigated and analyzed, and their analytical equations are also derived for application.

Keywords - independently controllable transmission (ICT), series-type, parallel-type, planetary gear train.

I. INTRODUCTION

Due to time varying characteristics of the wind, wind turbines usually provide fluctuating input speeds to the generator. This is because allowing the wind turbine to operate at a varying speed that is proportional to wind speed enables the aerodynamics of the rotor to be optimized. Therefore, variable speed wind turbines can better capture energy and yield higher power output and longer life. Consequently, optimizing aerodynamic performance will likely become a key component of future wind energy systems because of the prospect of increased performance and decreased costs [1-2].

Various electrical-mechanical designs have been proposed to enable operation at variable turbine speeds [3]. In the application of transmission mechanism, for example, Mangialardi and Mantriota proposed a wind power system having a continuous variable transmission to improve efficiency levels [4]. Idan and Lior presented the theory and design of a hybrid electro-mechanical variable speed wind turbine transmission and discussed a robust control solution for optimal power output [5]. Zhao and Maiβer proposed an electrically controlled power splitting drive train for variable speed wind turbines [6]. Müller et al., analyzed grid integration aspects of a new type of variable speed wind turbine that directly couples a synchronous generator with hydro-dynamically controlled gearbox, without the need for a power electronics converter [7]. Lahr and Hong proposed the cam-based infinitely variable transmission of ratcheting drive type to be utilized in variable speed wind turbines [8]. Hassan presented the methodology for enumeration of feasible clutching sequences of planetary gear mechanism composed of two or more fundamental gear entities [9].

In this study, a series-type independently controllable transmission (ICT) mechanism is proposed to control speed and torque transmission. The series-type ICT is an alternative form of the parallel-type mechanism proposed in the former researches [10-11]. It can produce a steady and required output speed that can be independently controlled and therefore does not depend on the angular velocity of the input power shaft. Applying the series-type ICT to variable speed wind power systems could overcome turbine speed fluctuations and provide constant speed input to the drive shaft of the generator to generate electricity with constant frequency. The proposed series-type ICT is composed of two planetary gear trains and two sets of transmission-connecting members. Kinematic and dynamic characteristics of the series-type ICT are investigated and analyzed, and their analytical equations are also derived for application.

II. STRUCTURE OF A SERIES-TYPE ICT

The conceptual design of the series-type ICT depicted in Fig. 1 consists of a mechanism with four rotational shafts, each possessing specific function, i.e., to connect to the input power source, the output power end, the controller, and a shaft referred to as the free-transmission end. In the application suggested here, the input power would be obtained from a wind turbine, and the output shaft would transmit power to a generator. A servo motor whose angular velocity is controllable would serve as a controller. The free-transmission end can be either a secondary power input source or an output, depending on the configuration of the mechanism and the speed ratio between the input and output shafts. The speed ratio between the output shaft and the controller is set as a constant and does not depend on the speed of the input shaft. Therefore, the required angular velocity of the output power shaft can be obtained by the

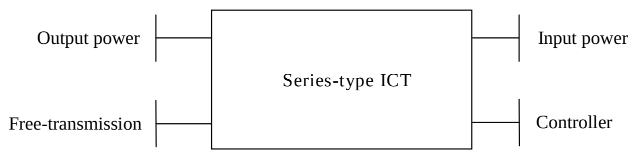

Fig. 1 Conceptual scheme of series-type ICT

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independent manipulation of the controller, regardless of the variation input shaft velocity.

The structure of the series-type ICT, as shown in Fig. 2, is composed of two planetary gear trains, denoted by *A* and *B*, and two sets of transmission-connecting members, indicated by *D* and *E*. As respectively depicted by *AD*, *OP*, *AE* and *BD*, *CR*, *BE*, each planetary gear train has three rotational shafts, i.e., the shafts of one sun gear, the carrier and the second sun gear meshed with the planet gears. In each planetary gear train, two of the three shafts are connected to the transmission-connecting members *D* and *E*, respectively. For example, shafts *AD* and *BD* are connected to the transmission-connecting member *D*, and shafts *AE* and *BE* are connected to *E*, as shown in Fig. 2. By means of shaft *SD*, the transmission-connecting member *D* can be connected to the source of input power, whereas the transmission-connecting member *E* can be connected to the free-transmission end by shaft *SE*. Finally, the third shaft of the planetary gear train *A*, i.e., *OP*, can be connected to the output power end, and the third shaft of *B*, i.e., *CR*, can be connected to the controller.

III. KINEMATIC ANALYSES OF A SERIES-TYPE ICT

A. Basic Requirements of Kinematics

To achieve the function and performance of the series-type ICT, the relationship of the angular velocities of shafts *AD* and *BD* shown in Fig. 2, which are used to transmit the input power respectively to the planetary gear trains *A* and *B*, can be established as

$$n_{BD} = \alpha\, n_{AD} \tag{1}$$

where n denotes the angular velocity of the rotational shaft indicated by its subscript, and α is a constant.

Since the angular velocity of the output shaft is independently manipulated by the controller and its velocity does not depend on the input power shaft, the relationship of the angular velocities of the shafts connected to the output end and to the controller, i.e., *OP* and *CR*, can be established as

$$n_{CR} = \beta\, n_{OP} \tag{2}$$

where β is a constant. The kinematic parameters α and β can be used to determine the speed ratios between the rotational shafts, and then the configuration of the ICT mechanism.

Finally, the angular velocities of the shafts *AE* and *BE* are established to be equal, i.e.

$$n_{BE} = n_{AE} \tag{3}$$

B. Positive-Ratio Planetary Gear Train

A positive-ratio planetary gear train, used in this study and shown in Fig. 3, includes a first sun gear *ps*1 mounted on the rotational shaft *pss*1, a second sun gear *ps*2 mounted on the rotational shaft *pss*2, at least one compound planet gear set including gears *pp*1, *pp*2, as well as meshing with the first and second sun gears, and a planet gear carrier *pa*. A positive-ratio planetary gear train means that the shafts of the first and second sun gears, when the carrier is fixed, have the same direction of rotation. Therefore, its basic speed-ratio, which is defined as the ratio of the relative velocities of the two sun gears' shafts respectively with respect to the carrier, is consequently positive and cannot be equal to 1 [12]. The basic speed-ratio of a positive-ratio planetary gear train, denoted by i_0, can be also mathematically expressed as

$$i_0 = \frac{n_{pss1} - n_{pa}}{n_{pss2} - n_{pa}} = \frac{N_{pp1} \times N_{ps2}}{N_{ps1} \times N_{pp2}} \tag{4}$$

where N is the teeth number of the gear indicated by its subscript. Rearranging Eq. (4) also yields

$$n_{pss2} = \frac{n_{pss1} - (1 - i_0) n_{pa}}{i_0} \tag{5}$$

C. Transmission-Connecting Member

A transmission-connecting members used in this study is shown in Fig. 4. The transmission-connecting member comprises gears *cmg*1 and *cmg*2 mounted on rotational shaft *cms* which can be used to connect to either the source of input power or the free-transmission end. Gears *cmg*1 and *cmg*2 are used to respectively connect with the shafts coming from the two planetary gear trains *A* and *B*. The capability of shaft *cms* is similar to that of the shaft *SD* or *SE* shown in Fig. 2, and the shafts coming from the two planetary gear trains *A* and *B* are just the shafts *AD*, *BD* or *AE*, *BE* shown in Fig. 2, respectively.

D. Arrangement of the Series-Type ICT

A practical arrangement of the series-type ICT is schematically shown in Fig. 5. In this ICT arrangement, both the planetary gear trains *A* and *B* are positive-ratio types shown in Fig. 3, and the transmission-connecting members *D*

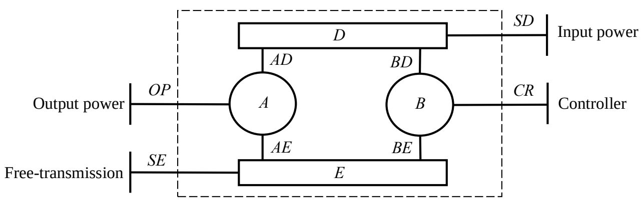

Fig. 2 Structure of series-type ICT.

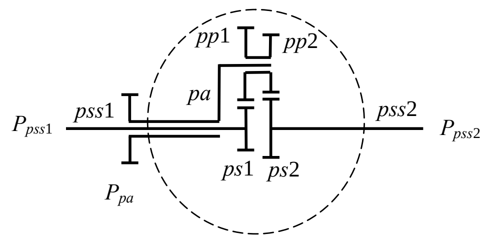

Fig. 3 Positive-ratio planetary gear train

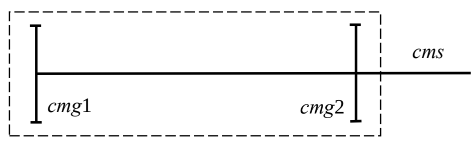

Fig. 4 Transmission-connecting member.

and E are as the one shown in Fig. 4. In the planetary gear trains A and B, the shafts of the first sun gears $pss1A$ and $pss1B$, similar to the shafts OP and CR shown in Fig. 2, are connected to the output power end and the controller, respectively. The function of the rotational shafts paA, $pss2A$, paB, and $pss2B$ are also similar to those of the shafts AD, AE, BD and BE, respectively. From the previous description, Eqs. (1)-(5) can be rewritten as follows:

$$n_{paB} = \alpha n_{paA} \tag{6}$$

$$n_{pss1B} = \beta n_{pss1A} \tag{7}$$

$$n_{pss2B} = n_{pss2A} \tag{8}$$

$$i_{0A} = \frac{n_{pss1A} - n_{paA}}{n_{pss2A} - n_{paA}} = \frac{N_{pp1A} \times N_{ps2A}}{N_{ps1A} \times N_{pp2A}} \tag{9}$$

$$i_{0B} = \frac{n_{pss1B} - n_{paB}}{n_{pss2B} - n_{paB}} = \frac{N_{pp1B} \times N_{ps2B}}{N_{ps1B} \times N_{pp2B}} \tag{10}$$

$$n_{pss2A} = \frac{n_{pss1A} - (1 - i_{0A}) n_{paA}}{i_{0A}} \tag{11}$$

$$n_{pss2B} = \frac{n_{pss1B} - (1 - i_{0B}) n_{paB}}{i_{0B}} \tag{12}$$

where i_{0A} and i_{0B} are the basic speed-ratios of the planetary gear trains A and B.

E. *Design Formulas of Series-Type ICTs*

Substituting Eqs. (6) and (7) into Eq. (12) yields

$$n_{pss2B} = \frac{\beta n_{pss1A} - (1 - i_{0B}) \alpha n_{paA}}{i_{0B}} \tag{13}$$

Referring to Eq. (8), the design formulas of the series-type ICT can be derived by equating Eqs. (11) and (13), and they are

$$\begin{cases} i_{0A} = \dfrac{\alpha - \beta}{\beta(\alpha - 1)},\ i_{0B} = \dfrac{\alpha - \beta}{\alpha - 1} & \text{if } \alpha \neq \beta, \alpha \neq 1 \text{ and } \beta \neq 1 \\ i_{0A} = i_{0B} & \text{if } \alpha = \beta = 1 \end{cases} \tag{14}$$

F. *Summary of Kinematics*

Basing on the description and discussion shown previously, the kinematic behavior of the series-type ICT can be summarized in this section. First according to Eq. (2) or (7), the angular velocity of the output power shaft can be obtained as

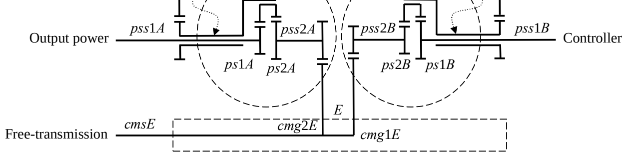

Fig. 5 Arrangement of series-type ICT.

$$n_{output} = \frac{1}{\beta} n_{controller} \tag{15}$$

where $n_{CR} = n_{pss1B} = n_{controller}$ and $n_{OP} = n_{pss1A} = n_{output}$.

Second, by substituting the results of Eqs. (11), (14), and (15), the angular velocity of the free-transmission shaft can be obtained as

$$\begin{aligned} n_{free-transmission} &= -\frac{N_{pss2A}}{N_{cmg2E}} \cdot n_{pss2A} \\ &= \frac{1-\alpha}{\alpha - \beta} \cdot \frac{N_{pss2A}}{N_{cmg2E}} \cdot n_{controller} + \frac{\alpha(1-\beta)}{\alpha - \beta} \cdot \frac{N_{pss2A}}{N_{cmg2E}} \cdot \frac{N_{cmg1D}}{N_{paA}} n_{input} \end{aligned} \tag{16}$$

where $n_{paA} = -\dfrac{N_{cmg1D}}{N_{paA}} \cdot n_{input}$.

IV. *DYNAMIC ANALYSES OF A SERIES-TYPE ICT*

In this study, an input shaft is defined as introducing a positive power into the ICT and consequently the torque and the speed have the same sense of rotation and carry the same sign. Conversely, an output shaft introduces a negative power while the torque and the speed carry opposite signs. The power introduced by the shaft of the ICT can be expressed as

$$P_X = T_X n_X \tag{17}$$

where P and T denote the power and torque introduced by the shaft indicated by its subscript, respectively.

A. *Power Flows and Torque Analyses of a Planetary Gear Train*

While neglecting friction losses, the sum of power introduced by a planetary gear train shown in Fig. 3 will be zero according to the conservation of energy, i.e.

$$\sum P = P_{pss1} + P_{pss2} + P_{pa} = 0 \tag{18}$$

In a stationary operating condition, a planetary gear train will also yield the equilibrium condition that the sum of all external torques acting on the shafts is equal to zero, i.e. [12-13]

$$\sum T = T_{pss1} + T_{pss2} + T_{pa} = 0 \tag{19}$$

By referring to Eqs. (4), (17)-(19), the following results can be also obtained:

$$T_{pss2} = -i_0 T_{pss1} \tag{20}$$

$$T_{pa} = (i_0 - 1) T_{pss1} \tag{21}$$

B. *Power Flows and Torque Analyses of a Series-Type ICT*

When considering the series-type ICT shown in Fig. 5 and referring to Eq. (7), the power introduced by the controller shaft can be expressed as

$$\begin{aligned} P_{controller} &= T_{controller} n_{controller} = T_{pss1B} n_{pss1B} \\ &= \beta T_{pss1B} n_{pss1A} \end{aligned} \tag{22}$$

The input power is transmitted into the planetary gear trains A and B by the shafts paA and paB, therefore it can be expressed as

$$P_{input} = T_{input}n_{input} = T_{cmsD}n_{cmsD} = T_{paA}n_{paA} + T_{paB}n_{paB} \tag{23}$$

Referring to Eqs. (14) and (21) yields

$$T_{paA} = (i_{0A} - 1)T_{pss1A} = \frac{\alpha(1-\beta)}{\beta(\alpha-1)}T_{pss1A} \tag{24}$$

$$T_{paB} = (i_{0B} - 1)T_{pss1B} = \frac{1-\beta}{\alpha-1}T_{pss1B} \tag{25}$$

By substituting the results of Eqs. (6), (24), and (25) into Eq. (23), the expression of the input power can be rewritten as

$$P_{input} = \frac{\alpha(1-\beta)}{\beta(\alpha-1)}T_{pss1A}n_{paA} + \frac{\alpha(1-\beta)}{\alpha-1}T_{pss1B}n_{paA} \tag{26}$$

The torque introduced by the shaft $pss1A$ can be derived by rearranging Eq. (26), i.e.

$$T_{pss1A} = \frac{\beta(\alpha-1)}{\alpha(1-\beta)}\cdot\frac{P_{input}}{n_{paA}} - \beta T_{pss1B} \tag{27}$$

Referring to Fig. 5, the output power transmitted by the series-type ICT can be expressed as

$$P_{output} = T_{output}n_{output} = T_{pss1A}n_{pss1A} \tag{28}$$

By substituting the result of Eq. (27) and referring to Eq. (22), Eq. (28) can be further rewritten as

$$P_{output} = \frac{\beta(\alpha-1)}{\alpha(1-\beta)}\cdot\frac{n_{pss1A}}{n_{paA}}P_{input} - P_{controller} \tag{29}$$

Referring to Fig. 5, the power introduced by the free-transmission end is

$$P_{free-transmission} = T_{free-transmission}n_{free-transmission} = T_{cmsE}n_{cmsE} = T_{pss2A}n_{pss2A} + T_{pss2B}n_{pss2B} \tag{30}$$

By substituting the result of Eq. (14) into Eqs. (11) and (20) also yields

$$n_{pss2A} = \frac{1}{i_{0A}}\cdot n_{pss1A} + \frac{i_{0A}-1}{i_{0A}}\cdot n_{paA} = \frac{\beta(\alpha-1)}{\alpha-\beta}\cdot n_{pss1A} + \frac{\alpha(1-\beta)}{\alpha-\beta}\cdot n_{psA} \tag{31}$$

$$T_{pss2A} = -i_{0A}T_{pss1A} = \frac{\beta-\alpha}{\beta(\alpha-1)}T_{pss1A} \tag{32}$$

$$T_{pss2B} = -i_{0B}T_{pss1B} = \frac{\beta-\alpha}{\alpha-1}T_{pss1B} \tag{33}$$

Substituting the results shown in Eqs. (31)-(33) into Eq. (30) and referring to the results of Eqs. (8) and (27) can rewrite the equation of the power introduced by the free-transmission end, i.e.

$$P_{free-transmission} = \left(\frac{\beta(\alpha-1)}{\alpha(\beta-1)}\cdot\frac{n_{pss1A}}{n_{paA}} - 1\right)P_{input} \tag{34}$$

C. Summary of Dynamics

Basing on the description and discussion shown previously, the dynamic behavior of the series-type ICT can be summarized in this section. First, the power flows of the series-type ICT can be shown in Eqs. (29) and (34).

Second, the output torque transmitted by the output power shaft can be further obtained from Eq. (27), i.e.

$$T_{output} = T_{pss1A} = \frac{\beta(\alpha-1)}{\alpha(\beta-1)}\cdot\frac{N_{paA}}{N_{cmg1D}}T_{input} - \beta T_{controller} \tag{35}$$

Third, the torque introduced by the free-transmission shaft can be also obtained by referring to the results of Eqs. (16) and (34), i.e.

$$T_{free-transmission} = T_{cmsE} = \frac{\alpha-\beta}{\alpha(\beta-1)}\cdot\frac{N_{cmg2E}}{N_{pss2A}}\cdot\frac{N_{paA}}{N_{cmg1D}}\cdot T_{input} \tag{36}$$

V. CONCLUSION

This study proposes an innovative design of the series-type ICT. The kinematic and dynamic analyses of the series-type ICT are investigated and their analytical equations are derived. The ICT mechanism can produce a required output angular velocity, which is independently manipulated by a controller and not affected by the input angular velocity. It also means that the series-type ICT can overcome the input speed fluctuations and provide a steady-speed output. By means of its kinematic characteristics, the series-type ICT also shows the possibility of application that it can transmit a steady-speed output to a generator to generate the electricity with stable frequency while being applied to variable speed wind turbines. Further researches about the performance and application of the series-type ICT are also proceeding.

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