Design of a new separable rotary transformer

X F Gong¹, L Zhang¹ and E J Feng¹

¹ School of mechanical engineering, University of Science & Technology Beijing, Beijing, China
bkjxzhangli@163.com

Abstract. A new-type separable rotary transformer which can be used in rotary steerable drilling is designed to deliver power efficiently from a stationary primary source to a rotary secondary load over a relatively large air gap via magnetic coupling. In this paper, E-type magnetic cores are reasonably distributed so that rotation of the rotary secondary has the least influence on reluctance of magnetic coupling. The influence of different winding layouts and connection modes on self-inductance and coupling coefficient is studied. By analysing the influence of the different geometrical shapes of cores on magnetic path, a design principle is proposed.

1. Introduction
Rotary steerable drilling and Logging While Drilling(LWD) system represent the highest level of drilling technology in today's world. Hydraulic driving mechanism of rotary steerable system is placed in the straightening looper, and the required electric energy is supplied by a mud generator on the drill collar, while there is relative rotation between straightening looper and drill collar [1-6]. Traditionally, slip ring is used to realize energy transfer in the rotating and non-rotating part. However, underground operating environment is so harsh that the slip ring frays easily with the strong shock and vibration, and its life and reliability will decrease [7].

In this paper, a new-type separable rotary transformer is designed. E-type magnetic cores are arranged in the outer surface of drill collar spindle and inner surface of straightening looper, forming a closed magnetic path between the outer surface core and inner surface core. In this design, coupling coefficient remains the same under relative rotation, which ensures the stability of the transmission efficiency.

2. Separable transformer design
The new mechanical structure of separable transformer is shown in Figure 1. On the inner cylindrical surface of stator and outer surface of rotor, respectively, with machining methods, a number of evenly spaced rectangular grooves are created around the axis of the circular surface, which are filled with E-type ferrite cores. Stator and rotor cores together constitute a transformer flux loop.

2.1. Core design
Since the magnetic core of the transformer are not continuously distributed, magnetic resistance may change when the rotor rotates, which will affect the system transmission efficiency. Therefore, number and width of cores are reasonably designed to ensure the stability of magnetic resistance while rotating. Core’s cross-sectional area and window area will influence the output power.
2.1.1. Core width angle design. The core width angle and core number must meet the formula (1) to ensure that magnetic resistance shouldn’t be affected by rotation of rotor.

\[
\begin{cases}
0 < \theta < \frac{360}{m} \\
0 < \theta < \frac{360}{n} \\
\theta = k \frac{360}{p}, k = 1, 2, 3...
\end{cases}
\]  

(1)

m, n are respectively the number of rotor and stator cores; p is the least common multiple of m, n; \( \theta \) is the angle of a single core width to the axis (core width angle).

Change of magnetic resistance can be measured by the angle of the coincident part of primary and secondary core to axis (\( \theta_c \), core coincidence angle). Figure 2 shows the effect of rotor rotation angle \( \theta_r \) on core coincidence angle \( \theta \), when \( m = 20, n = 24 \). When the core width angle doesn’t meet the formula (1), such as \( \theta = 7.5^\circ, 10.5^\circ \), the change of \( \theta \) caused by the rotation is up to 9\(^\circ\); When the core width angle meets the formula (1), such as \( \theta = 9.0^\circ, 12.0^\circ \), \( \theta_r \) is substantially unaffected by rotation of the rotor, which ensures effective cross-sectional area and magnetic reluctance constant.

Figure 1. Separable rotary transformer.

Figure 2. The relationship between coincidence angle, rotary angle and core width angle.

Increasing core utilization \( \eta \) is an important way to improve the transmission efficiency of the transformer. Core utilization can be described as following:

\[
\eta = \frac{\theta_r}{m \theta}
\]  

(2)

Table 1 shows the relationship between core utilization and core width angle when \( m = 20, n = 24 \). It can be seen that the utilization increases along with the core width angle, but the rotor’s mechanical
structure strength decreases simultaneously. Therefore, core width angle should not be too large, \( \theta = 9 \) is recommended in this paper.

**Table 1.** The relationship between core utilization and core width angle.

| \( \theta / ^\circ \) | 3   | 6   | 9   | 12  | 15  |
|------------------|-----|-----|-----|-----|-----|
| \( \theta / ^\circ \) | 12  | 48  | 108 | 192 | 300 |
| \( \eta / \% \)    | 20  | 40  | 60  | 80  | 100 |

2.1.2. Core cross-sectional area and window area design. Assuming that the input voltage of the system is sinusoidal, the sectional area of the magnetic core can be described as:

\[
A_n = \frac{V_{wp}}{4.44\eta NB_n}
\]

Where \( N \) is winding turn; \( B_n \) is saturation magnetization.

The formula (3) shows \( A_n \) relates to the peak input voltage \( V_{wp} \) and operating frequency \( f \). When \( V_{wp} \) is constant, \( A_n \) can be adjusted by changing \( f \) to adapt to different working space.

Core window area \( W_a \) is as following:

\[
W_a = \frac{V_{wp}I_p + V_{wp}I_s}{4.44\eta mK_f B_n J A_n}
\]

Where \( K_u \) is the core window utilization; \( J \) is the maximum current density; \( I_p, I_s \) are respectively the primary and secondary current amplitude [8].

The formula (4) shows the core size is determined by the primary and secondary apparent power.

2.2. Winding design

Separable transformer belongs to loosely coupled transformer, which has large leakage inductance, low coupling coefficient and low transmission efficiency. Winding layout and connection will affect electrical parameters of the transformer, so appropriate winding layout and connection can improve transmission efficiency.

2.2.1. Winding layout selection. There are two winding layout schemes. One is that the primary and secondary windings are radially separated as shown in Figure 3(a); the other is that windings are radially staggered as shown in Figure 3(b) [9].

![Figure 3. Winding layout.](image)

(1) Separated layout. According to the winding position in the core window, separated layout can be subdivided into axially spaced and radially spaced layout as shown in Figure 4(a) and 4(b).
Simulation results of ANSYS Maxwell are shown in Figure 5 and Figure 6. Winding axial movement distance has little effect on self-inductance, mutual inductance and coupling coefficient as shown in Figure 5; as shown in Figure 6, the larger the winding radial distance is, the smaller the gap becomes, and the larger the coupling coefficient is. Thus, coupling coefficient can be increased by reducing winding radial distance.

Figure 5. The effect of winding axial position on coupling coefficient.

Figure 6. The effect of winding radial position on coupling coefficient.

(2) Staggered layout. As shown in Table 2, compared with the radial separated layout, rotor and stator windings of staggered layout have smaller interval, lower leakage inductance and higher coupling coefficient, but the staggered layout has complex winding process, low reliability and is easy to wear. Therefore, the radial separated layout is recommended with minimizing the winding radial distance.

|                      | self-inductance $L_s / \mu H$ | mutual inductance $M / \mu H$ | coupling coefficient |
|----------------------|-------------------------------|-------------------------------|----------------------|
| Staggered layout     | 158.58                        | 149.49                        | 0.94                 |
| Radial separated     | 172.18                        | 123.06                        | 0.71                 |

2.2.2. Winding Connection Options. E-cores have four wire connection ways in the two windows as shown in Figure 7: Series with same direction, series with opposite direction, parallel with same direction, parallel with opposite direction. When wire connects in same direction, the magnetic flux is along upper, lower and sides of the magnetic circuit as shown in Figure 7a, 7c; When connecting in opposite direction, the flux is along upper and lower windows of the magnetic circuit as shown in Figure 7b, 7d.
Table 3 shows the measured inductance values of four kinds of connection ways when the air gap is 3 mm. As can be seen from the table: series with same direction connection has maximum value of inductance; parallel with opposite direction has the minimum; inductance of connecting with same direction is higher than with opposite direction.

**Table 3.** Inductance comparison of four wire connection ways.

| Connection Way                      | Self-inductance \( L_s / \mu H \) | Mutual Inductance \( M / \mu H \) | Coupling Coefficient |
|-------------------------------------|-----------------------------------|-----------------------------------|----------------------|
| Series with same direction          | 1310.3                            | 953.9                            | 0.75                 |
| Series with opposite direction      | 674.7                             | 327.7                            | 0.51                 |
| Parallel with same direction        | 324.6                             | 234.8                            | 0.74                 |
| Parallel with opposite direction    | 169.6                             | 80.9                             | 0.50                 |

**Figure 7.** The ways of winding connection

(a) Series with same direction

(b) Series with opposite direction

(c) Parallel with same direction

(d) Parallel with opposite direction
To improve the power transfer efficiency, a connection way with high inductance and low leakage inductance is feasible, such as series with same direction and series with opposite direction. Material of drill collar has a certain permeability and conductivity, series with opposite direction mode generates equal and opposite vortex in two windows, which can cancel each other out and improve the transmission efficiency. Therefore, the connection way of series with opposite direction is recommended in this paper.

3. Core size optimization

Reducing the leakage inductance of the transformer and improving inductance and coupling coefficient can effectively improve the transmission efficiency. Theoretical derivation and finite element analysis method are used to optimize the core geometry here.

The magnetic circuit of series with opposite direction mode is shown in Figure 8, since the magnetic circuit A, B of the upper and lower windows are symmetrical, it’s feasible only to study magnetic circuit A [10].

![Figure 8. Magnetic circuit of series with opposite direction mode.](image)

3.1. Magnetizing inductance

To simplify the model, by ignoring the flux of air gap edge, the magnetizing inductance of circuit A is as following:

$$L_{ma} = \frac{N^2}{\mu_0 A_n \left( \frac{l_m}{\mu} + 2l_e \right)}$$

(5)

Where N is primary winding turns; $\mu_0$ is air permeability; $\mu$ is relative permeability of Mn-Zn ferrite; $l_m$ is length of excitation magnetic path; $l_e$ is length of the air gap.

Magnetizing inductance of the transformer is twice of $L_{mA}$. As relative permeability is generally up to 2500~3000, $l_m/\mu << 2l_e$, magnetizing inductance is mainly decided by air gap length [11].

3.2. Leakage inductance

As shown in Figure 8, leakage flux mainly distributes in the rotor window (as $A_r$) and the air gap (as $A_g$). Leakage inductance can be calculated as following:

$$L_l = \frac{2}{3} \mu_0 \eta \mu_n f_c N^2 l_0 + l_e h_c$$

(6)

Where $\eta$ is the core utilization; $f_c$ is the core width; $h_c$ is the core window height; $l_0$ is the width of the core window; $l_e$ is the air gap length.

As $l_0 << l_e$, flux leakage is mainly decided by $h_c$ and $l_0$.

3.3. Size Optimization
Transformer coupling coefficient can be calculated as following:

\[
k = \frac{L_{m}}{L_{m} + L_{lk}} = \frac{1}{1 + \frac{2}{3} \eta mf l_{s} l_{m} l_{l} \frac{h_{s}}{A_{c} h_{c}}}
\]  

(7)

Formula (7) shows that increasing magnetizing inductance and reducing leakage inductance can effectively improve the coupling coefficient.

From formula (5), the magnetic energy of the excitation circuit mainly distributes in the core gap, reducing air gap can reduce the reluctance of the excitation magnetic circuit and increase magnetizing inductance. From the formula (6), the magnetic field energy of leakage magnetic circuit is mainly in the window, increasing the core window height and reducing the core width can improve the reluctance of magnetic flux leakage and reduce leakage magnetic flux.

To further analyse the influence of the air gap and height of the window on the transformer inductance, mutual inductance and coupling coefficient, setting \( \Delta = h_{s} / l_{s} \), ANSYS Maxwell is used to simulate how parameters of transformer change when only \( \Delta \) changes.

As shown in Figure 9, inductance and coupling coefficient are more sensitive when \( \Delta < 2 \); when \( \Delta = 2 \), the length of the air gap of excitation magnetic path and the leakage path are approximately equal, \( L_{m} \approx L_{lk} \), \( k \) is nearly 50%; When \( \Delta > 2 \), the change rate of inductance and coupling coefficient gradually reduce, and with the increase of \( \Delta \), core’s volume gradually increases. Therefore, the height of E-type core window must be more than twice of air gap width.

![Figure 9. The relationship between the inductance of transformer and \( \Delta \).](image)

4. Epilogue

The theoretical analysis, simulation and experimental results show that the inductance of transformer can avoid the interference of rotor’ rotation; the winding’s radial separated layout and series with opposite direction connection mode can improve the coupling coefficient and reduce the eddy current loss. The core cross-sectional area and the window area should be designed according to formula (3) and (4), minimizing the air gap and complying with the principle that the height of E-type core window must be more than twice of the air gap width.

References
[1]  Dai Yan, Flourish, Su Yugang, Tangchun Sen, et al. Study [J] non-contact power two-way push mode. China CSEE, 2010, 18: 55-61.
[2]  Zhang Zongming non-research [D] contactless power transmission system electromagnetic mechanism. Chongqing University, 2007.
[3]  Huang Xueliang, Tan Linlin, Chen, and other wireless power transmission technology research and application review [J] Electrical Technology, 2013, 10: 1-11.
[4] The full-Ru Dai, Xie light Yong, Wang Lin, a non-contact power transmission system based on electromagnetic coupling mechanism [J] college physics experiment, 2009, 04: 1-3.

[5] Cheng Shijie Chen Xiaoliang, Wang Junhua, and other key wireless transmission technology and its application [J] Electrical Technology, 2015, 19: 68-84.

[6] Qin Haihong, PROCEEDINGS, Yan Yangon non-contact analysis and design principles of loosely coupled inductive power transfer system [J] Power Technology, 2004, 05: 257-262.

[7] Zhou Wentao. Contact mechanics characteristics and wear life slip ring analysis [D]. Xiangtan University, 2014.

[8] YH Kim, KH Jin.Design and Implementation of a Rectangular-Type Contactless Transformer[J]. Industrial Electronics IEEE Transactions on, 2011, 58(12): 5380-5384.

[9] Phaengkieo D, Somlak W, Ruangsinchaiwanich S. Transformer Design by Finite Element Method with DOE Algorithm[C] Electrical Machines and Systems (ICEMS), 2013 International Conference on. IEEE, 2013: 2219-2224.

[10] Lin Ning, Yao Ying Ying, Li Yuling, etc. inductively coupled power transfer system design [J] Zhejiang University: Engineering Science, 2012, 46 (2): 199-205. TA Stuart, RJ King, H Shamseddin.Rotary transformer design with fixed magnetizing and/or leakage inductances[J]. IEEE Power Electronics Specialists Conference, 1985, 22(5): 480-487.

[11] EE Landsman.Rotary transformer design[J].IEEE Power Electronics Specialists Conference, 1970: 139-152.