Optimal Design and Comparative Analysis of Different Configurations of Brushless Doubly Fed Reluctance Machine

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The simple and robust construction of reluctance machines and the fact that they need an unsophisticated control have reigned interest in these machines. The constructional modifications and new configurations such as brushless doubly fed reluctance machines (BDFRM) show superior performance compared to their traditional counterparts, especially in variable speed applications such as pumps and wind generators. The design of BDFRM is different from other machines, as there are unusual pole combinations of stator and rotor besides the absence of a winding on the rotor. The operation and performance of the machine greatly depends on the mutual interaction between the stator windings. This interaction is modulated by the rotor with increased saliency. This paper examines a few critical issues in the design of BDFRM. Design optimization is performed using the gradient method from non-linear programming for 6-4-2 pole and 8-6-4 pole configurations of BDFRM. The performance of these optimized machines is examined through finite element analysis employing MAXWELL 16 software and then compared with 2kW prototypes constructed for laboratory use. A comparative analysis of the two configurations are presented and experimental results show that the BDFRM with the 8-6-4 ducted rotor is superior to BDFRM with the 6-4-2 reluctance and ducted rotor configurations.

Keywords: BDFRM, ducted rotors, finite element analysis, optimization

1. Introduction

Synchronous and Induction machines are used in fixed and variable speed applications by using Power Electronic Converters (PECs). Doubly Fed Induction Machines (DFIM) are preferred in variable speed applications as speed change on either side of synchronous speed is possible. In DFIM rotor circuit losses and maintenance of slip rings are two major shortcomings which has put limit on its operation. Therefore a suitable alternative for this machine is necessary. A promising alternative is Brushless Doubly Fed Reluctance Machine (BDFRM) which offers the benefit of partially rated converter about 30% of machine rating as it has to deal with slip power only\(^{(1)}\). In addition to this other advantages of BDFRM are absence of rotor copper loss, elimination of slip rings etc. These advantages give BDFRM an edge over other machines\(^{(2)}\). Many researchers have investigated this unusual machine\(^{(3)-(10)}\). Certain design aspects of BDFRM are addressed in\(^{(7)-(9)}\) and control through different PECs are discussed in\(^{(12)-(13)}\). However a very limited literature only is available on BDFRM. Clear guidelines for optimal design of BDFRM cannot be found. Therefore this paper is aimed at the consideration of different issues involved in optimal design and operation of BDFRM.

The performance of the BDFRM is greatly dependent on its rotor geometry. Higher the saliency ratio better is the machine performance. The selection of rotor configurations based on critical performance parameters is carried out by using Finite Element Analysis and the effect of various rotor configurations on performance of BDFRM is also investigated. It is hoped that this study will help in exploring BDFRM for many industrial applications. The validation of design is carried out on two prototypes developed.

This paper covers fundamentals of BDFRM in Section 2. This is followed by design considerations in Section 3. Section 4 discusses design optimization of BDFRM. Modelling and analysis of machine using finite elements are described in Section 5 followed by prototype results and discussion in Section 6.

2. Brushless Doubly Fed Reluctance Machine

Many researchers and developers have shown keen interest in improving the performance of plain reluctance machine whose rotor\(^{(12)}\) is shown in Fig. 1(a). By employing any one of the rotor configurations shown in Fig. 1(b)–(c) saliency ratio can be increased resulting in improved performance of the machine.

The conceptual arrangement of BDFRM is shown in Fig. 2. The stator has two sets of sinusoidally distributed windings namely power and control winding having ‘p’ and ‘q’ pairs of poles respectively. The rotor has \(P_r\) poles and is given by (1).

The control winding is excited by dc or variable frequency ac supply during operation whereas power winding is fed by local grid supply.
3. Design Considerations in BDFRM

The factors considered in design of BDFRM are choice of rotor, number of poles, specific loadings and other operational issues such as unbalanced magnetic forces and generation of harmonics. These are addressed in literature \(^{(14)-(16)}\). However there are a few other considerations which need to be explored in detail:

1. Choice of windings (single or two independent windings).
2. Stator winding pitches (in case of two windings).
3. Selection of power winding.
4. Factors affecting length of air gap.
5. Operating range of frequency and voltage of control winding.
6. Issues such as unbalanced magnetic pull, space harmonics, noise, bearing currents and reduction in losses.

The critical parameters in design are choice of electric and magnetic loading. The optimal values of these are obtained iteratively. The process of design is complex with optimization at many levels. Usually in optimal design process definition of objective function, constraint function and independent variables are required \(^{(17)}\). The objective functions can be cost of active material required, or overall weight/dimensions or performance parameters. Since consideration of all variables is impracticable only those parameters having significant impact on overall performance of machine are considered. These independent variables \(^{(18)}\) are given below:

- Stator bore diameter, gross iron length of stator, width of stator slot, height of stator slot, height of stator yoke, minimum length of air gap, maximum length of air gap, number of stator slots, number of turns per pole per phase and cross sectional area of conductors.

It is assumed that independent variables are continuous in nature to simplify the problem though some variable can be discrete type such as number of slots and conductor cross section. In addition variables such as slot opening, lip height, wedge height etc. are assumed to be known.

4. Design Optimization of BDFRM

The rating of proposed machine was fixed as 2 kW. The constraint functions and limits considered are:

- Maximum torque ≥ 1.5 time full load torque
- Full load power factor ≥ 0.5 lagging
- Current density ≤ 4.5 A/mm\(^2\)
- Slot fill factor ≤ 65%.
- Maximum tooth flux density ≤ 2 T
- Maximum flux density in stator core and yoke ≤ 1.3T
- Specific electrical loading ≤ 25000 amperes cond/m
- Width of stator slot ≥ 6 mm
- Temperature rise ≤ 50°C
- Shaft diameter ≥ 25 mm

Insulation class F is employed in BDFRM windings. The temperature rise constraint is kept as 50°C even though the allowable temperature rise for class F insulation is 115°C \(^{(19)}\). This is to allow for hotspot temperature and increased safety for insulation and winding.

The objective function (7) can be formulated by using (4), (5) and (6).

\[
V_{is} = L_4[\pi (x_1 + x_4 + x_6)^2 - \pi x_1^2 - x_3 x_4 x_10] \quad (4)
\]

\[
V_{fr} = 0.9 x_2 (\pi d_f^2 + 4(x_7^2 \theta - \cos \theta \sin \theta)) \quad (5)
\]

\[
V_c = 2(p mx x_9 L_{amp} + qmx x_9 L_{v}) \quad (6)
\]

\[
F = D_p (V_{is} + V_{fr}) + D_v V_c \quad (7)
\]

where

\[
L_4 = 0.9(x_2 - n_d d_4)
\]
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Table 1. Particulars of Optimized 6-4-2 reluctance rotor BDFRM

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>6-4-2 combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gap flux density</td>
<td>0.73 T</td>
</tr>
<tr>
<td>2</td>
<td>Current density</td>
<td>4.5 A/mm²</td>
</tr>
<tr>
<td>3</td>
<td>Rotor diameter</td>
<td>89.71 mm</td>
</tr>
<tr>
<td>4</td>
<td>Stack length</td>
<td>75 mm</td>
</tr>
<tr>
<td>5</td>
<td>Slot width</td>
<td>7.76 mm</td>
</tr>
<tr>
<td>6</td>
<td>Slot depth</td>
<td>23.04 mm</td>
</tr>
<tr>
<td>7</td>
<td>Depth of stator core</td>
<td>8.4 mm</td>
</tr>
<tr>
<td>8</td>
<td>Outer diameter of stator lamination</td>
<td>165 mm</td>
</tr>
<tr>
<td>9</td>
<td>Weight of copper</td>
<td>2.494 kg</td>
</tr>
<tr>
<td>10</td>
<td>Weight of stator core</td>
<td>2.263 kg</td>
</tr>
<tr>
<td>11</td>
<td>Weight of stator teeth</td>
<td>2.123 kg</td>
</tr>
<tr>
<td>12</td>
<td>Power factor</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Table 2. Particulars of Optimized 8-6-4-ducted rotor BDFRM

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>8-6-4 combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gap flux density</td>
<td>0.5 T</td>
</tr>
<tr>
<td>2</td>
<td>Current density</td>
<td>4.0 A/mm²</td>
</tr>
<tr>
<td>3</td>
<td>Rotor diameter</td>
<td>145.33 mm</td>
</tr>
<tr>
<td>4</td>
<td>Stack length</td>
<td>91 mm</td>
</tr>
<tr>
<td>5</td>
<td>Slot width</td>
<td>8.21 mm</td>
</tr>
<tr>
<td>6</td>
<td>Slot depth</td>
<td>19.03 mm</td>
</tr>
<tr>
<td>7</td>
<td>Depth of stator core</td>
<td>6.99 mm</td>
</tr>
<tr>
<td>8</td>
<td>Outer diameter of stator lamination</td>
<td>210 mm</td>
</tr>
<tr>
<td>9</td>
<td>Weight of copper</td>
<td>3.783 kg</td>
</tr>
<tr>
<td>10</td>
<td>Weight of stator core</td>
<td>2.99 kg</td>
</tr>
<tr>
<td>11</td>
<td>Weight of stator teeth</td>
<td>2.64 kg</td>
</tr>
<tr>
<td>12</td>
<td>Power factor</td>
<td>0.803</td>
</tr>
</tbody>
</table>

In this paper MAXWELL-16 software is used for developing the analytical models of BDFRM and simulated by using small time steps. For analysis BDFRM having same power rating but different pole configurations are used.

The finite element models are developed from the actual dimensions of stator and rotor laminations for 6-4-2 and 8-6-4 configurations shown in Fig. 4(a) and Fig. 4(b) respectively.

The exterior dimensions of stator and rotor are kept constant only rotor geometry is varied to get different configurations of BDFRM.

Figure 5(a) shows 6-4-2 configuration of BDFRM with reluctance rotor. It can be noted that the flux density in this configuration stays within the limit which has avoided saturation in magnetic circuit of the machine.

Additional models of BDFRM with advanced rotors are developed. Figure 5(b) shows 6-4-2 pole combination BDFRM with axially laminated anisotropic (ALA) rotor having 4 poles. Figure 5(c) shows model of 8-6-4 pole combination with reluctance rotor and Fig. 5(d) indicate model of 8-6-4 pole combination with ALA rotor. Though improved performance can be obtained from ALA rotor but it is not constructed due to constructional difficulties and high cost.

A comparable performance can be achieved by employing ducted rotor which is cost effective. Therefore a model of circular ducted rotor 8-6-4 combination is developed as shown in Fig. 5(e) for simulation study and fabrication.

The simulation study is carried out with both windings excited. The flux density distribution in the machines are shown in Fig. 5(a) to Fig. 5(e). The flux distribution in axial lamination is fairly uniform which avoids saturation in stator magnetic circuit. It is observed that the flux density

V_is – volume of iron in stator, Di – density of iron, L_i – net iron length, x1 – radius of stator bore, x2 – gross length of stator, x3 – width of stator slot, x4 – depth of stator slot, x5 – depth of yoke, x10 – number of slots in stator, x11 – number of ventilating ducts, b12 – width of ventilating duct, V_re – volume of iron in rotor, d_r2 – rotor diameter at maximum air gap, θ – angle subtended by pole arc, V_c – volume of copper in machine, D_c – density of copper, p – number of pole pairs, x5 – cross sectional area of stator conductor, x9 – number of turns/pole/phase, L_mtp, L_mts – length of mean turn for power and control winding respectively.

The flowchart of design synthesis is shown in Fig. 3.

4.1 Optimized BDFRM The process of design is based on gradient method in nonlinear programming. The results of optimization of a 2 kW, 220 V, three phase, 50 Hz BDFRM for 6-4-2 configuration and 8-6-4 configuration are given in Table 1 and Table 2 respectively.

5. Simulation Studies and Results

Mathematical tools like finite element methods prove to be useful in analysis of designed machine especially for complex part like magnetic circuits. Some commonly used software are SPEED, FLUX, INFOLYTICA and MAXWELL.
in tooth section for 6-4-2 combination with reluctance rotor (Fig. 5(a)) has reached to a peak value of 1.77T. For 8-6-4 configuration with reluctance rotor flux density do not exceed 1.48T. The peak magnitudes of flux densities in 6-4-2 ALA rotor and 8-6-4 ALA rotor do not exceed 1.5T and 1.1T respectively which can be seen from Figs. 5(b) and (d). The flux density in different parts of 8-6-4 ducted rotor BDFRM does not exceed 1.77T. Hence good performance can be expected from machine having higher pole configuration with advanced rotors either ALA or ducted rotor.

Reluctance machines invariably suffer from inferior and pulsating torque production. The torque developed by different configurations is therefore obtained by performing FEA analysis.

The torque-rotor position characteristics are obtained with power winding excited by 230 V, 50 Hz source and control winding excited with variable frequency excitation. The torque developed by 6-4-2 pole combination and 8-4-6 pole combination with reluctance rotor are shown in Fig. 6(a) and Fig. 6(b) respectively. The torque developed in both cases is of pulsating nature. Further it can be seen that wider fluctuations are observed for 6-4-2 configuration with inferior average torque. Though the torque developed by 8-6-4 configuration is also pulsating the average value is higher than 6-4-2 configuration.

The torque developed by 8-6-4 circular ducted rotor configuration is shown in Fig. 6(c) which clearly shows that torque developed by 8-6-4 configuration is steady and remains fairly
constant.

The simulation studies are carried for different values of control winding frequency. This is to select the desirable range of control winding frequency over which torque remains constant. The steps are given below:

1. Develop analytical model of BDFRM configuration under study.
2. Power winding (higher pole number winding) is excited by 230 V, 50 Hz supply.
3. Control winding is excited with variable frequency supply (5 Hz to 60 Hz). \( V_c/F_c \) is kept constant at the ratio equal to \( V_c \) (rated)/\( F_c \) (rated).
4. The phase sequence of control winding supply is kept same as that of power winding phase sequence.
5. For each setting of \( F_c \) instantaneous torque developed by the BDFRM is obtained from finite element analysis and its average value is calculated.
6. The average value of torque obtained is used for plotting the characteristic torque (pu) vs. control winding frequency (\( F_c \)).

Figure 7 shows that 6-4-2 axial rotor BDFRM develops negative average torque in the frequency ranges 0–10 Hz and 25–35 Hz. The negativity implies that this configuration is not suitable in the frequency range of 0–30 Hz. In 35 Hz–40 Hz average torque though positive is linearly increasing and not useful. From 40 Hz onwards it is nearly constant. Hence it can be seen from torque-frequency characteristics shown in Fig. 7 that the suitable range of frequency is 40 Hz–60 Hz over which torque remains fairly constant. There are considerable fluctuations in torque developed by 6-4-2 combination. At lower frequencies of control these may lead to unstable operation of machine.

The average torques developed at different speeds for different configurations is summarized in Table 3. It can be seen that average torque developed by 8-6-4 ducted combination is highest (35.54 N-m) with lowest torque ripple of 19%.

The flux linkages vs. current (\( \lambda-i \)) plots give an indication of performance of machine. The area enclosed in the \( \lambda-i \) loop represents the work done. Wider is the loop area better is the performance. The performance factors of the machine such as power factor, torque etc. can be estimated by using (\( \lambda-i \)) plot. For various configurations such plots are obtained with control winding frequency of 50 Hz, 50 V and power winding excited by 50 Hz, 230 V mains. The plots obtained are shown in Fig. 8.

It can be clearly seen from Fig. 8(d) that 8-6-4 axial rotor configuration has wider (\( \lambda-i \)) loop and hence the performance (Table 3).
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Fig. 8. \((\lambda-i)\) plots for BDFRM

will be better. Similarly the \((\lambda-i)\) loop for 8-6-4 ducted rotor configuration is closer to that of for axial rotor and hence comparable performance can be obtained from 8-6-4 ducted rotor BDFRM also.

Another significant parameter is the radial magnetic forces known as unbalanced magnetic pull acting on the rotor surface. The radial forces are function of air gap flux density. They also depends on length of air gap and mechanical quantities such as eccentricity. However under balanced rotor conditions and moderate air gap length these unbalanced magnetic forces are not noticeable. In case of BDFRM there is no counter balancing of stator MMF by rotor MMF as in other machines. Therefore unbalanced magnetic forces are inevitable. Further saliency in rotor circuits aggravates the situation. It is therefore necessary to study and investigate these forces. For different configurations of BDFRM unbalanced pulls are obtained from field analysis. Figure 9 shows the result.

It can be clearly seen that forces developed on reluctance rotor are greater and in 6-4-2 configuration it is highest. The axial rotor is found to reduce magnetic pull significantly. It is interesting to note that the characteristics shown in 9(a) and 9(d) are look similar even though these are for different rotor configurations. It may be emphasized once again that the unbalanced forces acting on rotor surface of 8-6-4 configurations are less in comparison with those of 6-4-2 configurations.

Some other issues related to BDFRM are also under investigation which may be reported in a future paper.

6. Experimental Results and Discussions

Out of different configurations simulated by using finite element analysis two combinations are short-listed for building prototypes. These are 6-4-2 reluctance rotor and 8-6-4 circular ducted rotor BDFRMs. The details along with test results are presented below.

6.1 BDFRM configuration: 6-4-2 reluctance rotor

It has a single stator winding which is arranged in 36 slots. Figure 10 shows the developed winding diagram where end connections are arranged such that one end connection behaves as a 6 pole winding and other end as 2 pole winding. The 6 pole winding is considered as power winding and the other one as control winding. Figure 11(a) shows the prototype BDFRM and Fig. 11(b) shows the experimental setup.

If voltage is applied to the power winding current flowing through it is fairly sinusoidal and so for the control winding. The current and voltage waveform of power winding is shown in Fig. 12. It can also be seen that input power factor of the machine is near about 0.7–0.8. It is observed that at standstill condition secondary winding induced emf due to
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(a) Unbalanced magnetic forces acting on rotor surfaces of two configurations of BDFRM.

(b) Rotor forces developed by salient rotor and axial configuration of rotor.

(c) Rotor surface forces developed by 8-6-4 combination.

(d) Rotor surface forces developed by two axial rotor configurations.

Fig. 9. Rotor forces developed in different BDFRM configurations

Transformer action has the same frequency as that of power winding. As rotor starts rotating speed emf gets superimposed on transformer emf. The resultant control winding induced emf waveform gets distorted having significant third harmonics as shown in Fig. 13. This may be due to different pole pitches in the winding. When BDFRM is excited from both sides with 50 Hz signals with the phase sequence of control winding different from that of power winding the currents drawn by both windings are shown in Fig. 14. It shows that control winding current has third harmonic component.

It is further observed that if excitation frequency of power winding is 49.6 Hz it attains the speed of 745 rpm. The synchronous speed is of 750 rpm for 6-4-2 combination for 50 Hz grid frequency. It is also noticed that the torque pulsations are accompanied with humming noise. These are required to be addressed in detail but are beyond the scope of this paper.

6.2 8-6-4 ducted rotor BDFRM

8-6-4 ducted rotor BDFRM is shown in Figs. 15(a) and (b). It clearly shows developed stator and ducted rotor construction with six prominent poles. The stator consists of two independent sinusoidally distributed, full pitched, double layer windings designed for eight and four poles respectively. As there are four layers of windings it necessitates deeper slots which increases stator outer diameter. The fabrication is carried out using design dimensions given in Table 2.

The prototype is tested for validation. One winding of the machine is excited at a time. When 8 pole winding is excited by sinusoidal supply at 49.5 Hz from the grid, the machine has attained a speed of 494 rpm. This agrees with the calculation using (2). The current and voltage waveforms are shown in Fig. 16. It can be seen that current drawn by 8 pole winding is sinusoidal.

Figure 17 shows the pulses obtained from the incremental encoder (Model: Delta ES3-11LG694) connected to 8-6-4 BDFRM. The encoder produces 1024 pulses per revolution. By using (8) actual speed is calculated for different conditions.

\[
\text{Speed of BDFRM} = \frac{\text{Frequency of pulses/PPR}}{60} \times 60
\]

For pulses shown in Fig. 17 are for grid frequency 49.5 Hz and inverter output frequency is 20 Hz. Therefore speed is calculated as 206 rpm using (8).

At standstill condition there is only transformer action and
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Fig. 11. Details of 6-4-2 prototype  

(a) Prototype 6-4-2 BDFRM.  

(b) Experimental setup.  

Fig. 12. Power Winding Voltage and current  

Fig. 13. Induced EMF in control winding (green), Power winding voltage.  

Fig. 14. Waveforms of power winding (magenta) current and control winding (blue) currents  

Fig. 15. Details of 8-6-4 prototype  

Fig. 16. 8 pole winding Voltage (green) and current (yellow) waveforms  

hence frequency of induced EMF is same as grid frequency as seen from Fig. 18. Under running conditions there is a mutual coupling between two windings. Therefore an EMF will be induced in each of the windings. The flux density in air gap gets modulated and therefore harmonic components get superimposed on induced EMF resulting in distortions. This can be seen from Fig. 19.

With dual excitation depending on the phase sequence of 4 pole winding speed of BDFRM can be varied. The voltage and current waveforms of control winding excited by inverter
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Fig. 17. Pulses of encoder connected to 8-6-4 BDFRM

Fig. 18. 8 pole voltage (yellow) and induced EMF (green) in 4 pole winding

Fig. 19. 8 pole applied voltage (yellow) and induced EMF (green) in 4 pole winding

are shown in Fig. 20(a). However under this condition power winding current waveform also gets modulated which can be seen from current (green) waveforms shown in Fig. 20(b).

6.2.1 Speed Control of 8-6-4 Ducted Rotor Configuration of BDFRM

For obtaining variable speed from 8-6-4 ducted BDFRM the test set up is shown in Fig. 21. A dc generator of rating 2 kW, 220 V, and 1500 rpm is used. The power winding is excited by grid and control winding is excited from an inverter. $V_c/F_c$ control is employed. The results are shown in Fig. 22. From the figure it can be seen that the ratio $(V_c/F_c)$ remains fairly constant.

The speed control of 8-6-4 poles BDFRM is achieved by variable frequency excitation of control winding. The power winding is excited at 400 V, 50 Hz grid and control winding through three phase voltage source converter (VSC). The phase sequence of output voltage of VSC if it is same as that of grid voltage frequency is considered as positive and with reverse phase sequence of voltage of VSC; frequency is considered to be negative. Figure 23 shows the speed verses control winding frequency characteristics showing that the speed of BDFRM can be controlled on the either side of rated speed of 500 rpm.

A load test is performed on 8-6-4 ducted rotor BDFRM with the experimental setup shown in Fig. 21. The control winding frequency is kept at 30 Hz and voltage at 140 V. The
Fig. 22. Results of $V_c/F_c$ control characteristics of a 8-6-4 configuration of BDFRM

Fig. 23. Speed control of 8-6-4 configuration of BDFRM

Fig. 24. Efficiency and power factor variation of BDFRM at grid frequency 50 Hz and control winding frequency 30 Hz

operating efficiency and power factor calculated from test results are presented in Fig. 24. In load test the efficiency and power factor obtained at 80% of the output obtained are 77% and 0.7 lagging respectively. As per the optimal design values of efficiency 82% and 0.8 lagging at full load condition. The load test could not be conducted at full load condition due to disturbances in the grid.

7. Conclusions

This paper highlights the operation of optimally designed 2 kW BDFRM prototypes.

1. Finite element models of 6-4-2 poles 8-6-4 poles combinations with reluctance and axial/ducted rotors are investigated.
2. Simulation studies show that the performance of 8-6-4 axial/ducted rotor configuration is superior. The peak value of flux density is within acceptable limit and there is no saturation of magnetic circuit. These configurations develop higher average torque with less ripples, less magnetic pull, less harmonic contents in the current and better power factor around 0.8 lagging.
3. The magnitude of unbalance magnetic pull is greatly reduced in axially laminated/ducted rotor in comparison with reluctance rotor.
4. Experiments show that both prototypes 6-4-2 configuration and 8-6-4 configuration rotate at a synchronous speed given by (2) and as dictated by the frequencies (measured values) of power winding and control winding. It is observed that the operation of 8-6-4 configuration is better. There is minimum noise and vibration due to lesser torque pulsations. The current waveform is better with reduced harmonic content.
5. With simultaneous excitation of both windings of 8-6-4 BDFRM variable speed is obtained using $V/F$ control. With reversing phase sequence of control winding speed control over 40% on either side of rated speed is achieved. The load test carried out on 8-6-4 configuration indicate that machine performance is satisfactory.

References

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