

## APPLIED RESEARCH

# 48-Volt Energy Efficient Domestic Appliances With Flux Switching Motor Drive System—Design, Simulation, and Comparison

**NATESAN CHOKKALINGAM LENIN<sup>ID</sup>**, (Senior Member, IEEE)

Electric Vehicles: Incubation, Testing and Research Centre, Vellore Institute of Technology, Chennai 600127, India

e-mail: lenin.nc@vit.ac.in

**ABSTRACT** Energy-Efficient domestic appliances are the need of the hour. This paper explores the importance of 48-Volt domestic appliances especially those operated with an electric motor drive system. Sixteen domestic appliances that are having a power range of 12–1600 Watt are selected. These appliances are usually produced in very large volumes; therefore, one of the most important requirements is efficiency with moderate cost. Commutator motors are widely preferred for those applications in the present commercial market, which lags in efficiency, requires more space and, bulkier. Flux Switching Motor (FSM) is a new variant in brushless direct current (DC) motor, which has a combined advantage of commutator, Switched Reluctance and, Permanent Magnet Brushless DC Motors (PMBLDC). Complete simulation results with the FSM drive system have been carryout and the performance is compared with the commutator DC motor (DCM) and Induction Motors (IM). Simulation results support FSM drive system technology and novel insights follow from this quantitative comparison.

**INDEX TERMS** 48-volt system, energy-efficient domestic appliances, flux switching motor.

## I. INTRODUCTION

A domestic appliance is a machine, which assists in household functions such as juicers, mixers, grinders, cooling, washing, cooking, cleaning, etc. to ease the human job. These appliances are divided into three types: (i) small appliances (ii) major appliances, or white goods and, (iii) consumer electronics, or brown goods. According to [1], electric kitchen appliances market volumes are expected to grow at a Compound annual growth rate (CAGR) of around 17-20% over the next five years.

Awareness about the environment and energy savings in electrical appliances are high as ever before with consumers. Energy-efficient devices save energy consumption considerably, led to reducing the adverse effects of global warming. Further to this, DC systems play a vital role in these energy-efficient domestic appliances.

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48-Volt DC is preferred for these appliances since, the feeder losses decrease substantially [2]. Moreover, the 48-Volt DC system with optimized cable area is the most economical system compared with the 230 Volt Alternating Current (AC) system and, with a 20 years lifetime, it will save almost United States Dollar (USD) 1560 [3]. Based on [4], the global smart home appliances market to grow by USD 31.66 billion, decelerating at a CAGR of over 16% during 2020-224.

New generations of household appliances must have higher performance such as reduced power consumption, increased efficiency, reduced electromagnetic interference, and with reasonable cost. DCM (in Figure 1(a) is preferred at large because of the proven technology whereas, driven by the efficiency and power density, Permanent Magnet based FSM (shown in Figure 1(b)) becomes a strong contender to the DCM [5].

FSM is a doubly salient motor. Two types of FSM are (i) field excited FSM (FEFSM) (ii) permanent magnet FSM (PMFSM). The design and analysis of the FSM are found

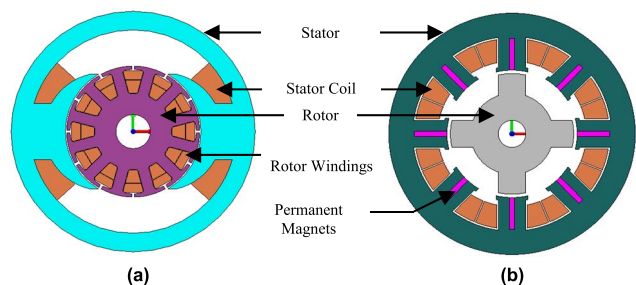


FIGURE 1. (a) DCM (b) PMFSM.

in [6]. The PMFSM has high torque density, high efficiency, and the most attractive from the FSM dynasty for many applications [7]–[11]. The speed and torque of both FSM can be controlled electronically [12], [13] in more efficient way.

Single-phase FEFSM has low cost, longer life, simple manufacturing and can be used for high-speed applications [14]. In [15], a novel model of single-phase FSM for fan application has been developed and tested. The impact of design parameters and its performance with its structural abilities are discussed in [16]. Muhammad Irfan *et al.* [17] developed a novel winding technology for FSM recently. Since, this article focused primarily on energy-efficient appliances, PMFSM is more suitable for the applications considered.

Section 2 provides a complete information on the targeted applications like Indian and global market trends, design specifications of the electric motor used, finite element simulation results, performance comparisons. Following are the applications considered for this study: (i) water purifier (ii) ceiling fan (iii) refrigerator (iv) air cooler (v) mixer-grinder (vi) hand blender (vii) hand mixer (viii) vacuum cleaner (ix) washing machine (x) dishwasher (xi) domestic juicer (xii) coffee machine (xiii) hairdryer (xiv) air-conditioner (ac) compressor (xv) ac condenser fan and (xvi) ac outdoor fan. Section 3 discusses conclusions with a wide comparison of the simulation results. Further to this, other possible applications of FSM are listed at the end of the conclusion.

**II. DOMESTIC APPLIANCES - MARKET TRENDS, DESIGN SPECIFICATIONS, SIMULATIONS AND COMPARISONS**

**A. WATER PURIFIER**

Increasing population, industrial proliferation, and environmental hazards are all causes of water contamination. A water purifier removes the excess salts, suspended particles, microbes, and retains its essential vitamins and minerals. Water Purifier Sales in India predicts to reach USD 4.8 billion by 2023 [18]–[20]. Based on technology, the market is classified into Ultraviolet (UV), Reverse Osmosis (RO), and gravity based. In 2019, the RO water purifier segment occupied the largest water purifier market share of 65.4%, followed by the UV segment with 20.7%,

and is expected to grow at the highest CAGR of 9.9% from 2019 to 2025. RO water purification systems are widely adopted across the globe, due to their performance efficiency, low electricity consumption, and regular technological innovation.

Based on end user, the market is categorized into commercial and residential. The residential user’s segment occupied a significant market share of 74.7% in 2018 and is expected to grow at a CAGR of 8.9% from 2019 to 2025. However, the commercial segment accounted for 25.3% market share in 2018 and is expected to grow at a CAGR of 10.4% in the near future [20]–[21].

TABLE 1. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	12	Watt
Rated Torque	0.15	Nm
Rated Speed	750	rpm
Outer Diameter	55	mm
Motor Stack Length	35	mm



FIGURE 2. Water purifier and its motor.

The selected purifier motor (in figure 2) is based on domestic RO, which requires a motor power of 12 Watt for its proper operation. Other technical specifications are tabulated in Table 1. DCM and PMFSM are designed for the required specification aiming for a lower cost. Hence, low-cost ferrite magnets are chosen for PMFSM designs (as well as throughout the other designs in this article). The designed motor cross section is depicted in figure 3. For all the discussed applications, M-36, a low cost silicon steel is used for both the stator and the rotor core design. Copper wire is preferred for windings. Detailed simulation results are compared in Table 2.

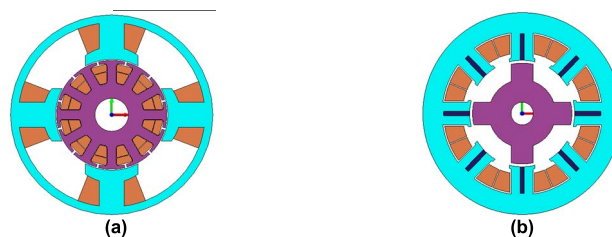


FIGURE 3. (A) DCM (B) PMFSM.

TABLE 2. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	19.2	17.1	Watt
Output power	12.22	12.343	Watt
Efficiency	63.64	72.19	%
Stator core mass	0.4428	0.369	kg
Rotor core mass	0.127	0.122	kg
Magnet mass	-	0.082	kg
Winding mass	0.2113	0.139	kg
Total mass	0.781	0.713	kg

**B. CEILING FAN**

Define A ceiling fan is an electrically functioned mechanical device that is suspended on the ceiling of a room to circulate air. It is composed of hub-mounted rotating paddles, an electric motor, and metal rods. It is largely preferred by consumers because of better shelf life, low power consumption, high energy-efficiency, and cost-effectiveness compare to air-conditioners. Ceiling fans are one of the heavily consumed electrical equipment in a country like India, and it consumed with around 20 to 30% of the total energy produced [22]. The global ceiling fan market size reached a value of almost USD 9.3 billion in the year 2020. The industry is further expected to grow at a CAGR of 3% between 2021 and 2026 to reach a value of almost USD 11.1 billion by 2026 [23].

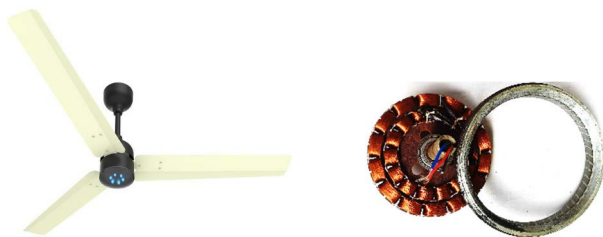


FIGURE 4. Ceiling fan and its motor.

Figure 4 shows the dismantled single-phase induction motor (SPIM) used in most of the fans. The proposed PMFSM is expected to consume less than 35 Watt of power at a speed of 350 rpm. Table 3 shows the technical specifications of the designed fan motor [24].

TABLE 3. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	20	Watt
Rated Torque	0.567	Nm
Rated Speed	350	rpm
Rotor Outer Diameter	114	mm
Motor Stack Length	16	mm

The designed motors for the required specification and simulation results are depicted in figure 5 and Table 4 respectively.



FIGURE 5. (a) SPIM (b) PMFSM.

TABLE 4. Performance comparison.

Parameter	SPIM	PMFSM	Unit
Input power	52	31	W
Output power	22.4	23.6	W
Efficiency	43.1	76.13	%
Stator core mass	1.320	0.569	kg
Rotor core mass	0.623	0.263	kg
Magnet mass	-	0.221	kg
Winding mass	0.208	0.201	kg
Total mass	2.195	1.017	kg

**C. REFRIGERATOR**

In most domestic refrigerators, an electric reciprocating compressor (ERC) is used to compress the refrigerant gas. In ERC, the motor and the reciprocating mechanism are hermetically sealed inside the frame. In India, the market size in value for refrigerators is expect to reach USD 5.34 billion by 2022 [25]. The global refrigerator market size was valued at USD 64.17 billion in 2018 and is projected to reach USD 103.95 billion by 2026, exhibiting a CAGR of 6.3% during the forecast period [26]. For cost reasons, most ERC is driven by SPIM, leading to a relatively low efficiency. In modern, high-efficiency-class refrigerators, the ERC prefers PMBLDC, leading to a higher overall manufacturing cost. Hence, industries are looking for an alternative low-cost, high-efficiency, robust motor technology combining the best of SPIM and PMBLDC. A promising technology is the proposed PMFSM. Figure 6 shows the dismantled refrigerator compressor. Technical specifications of the chosen refrigerator motor are tabulated in Table 5 [27].

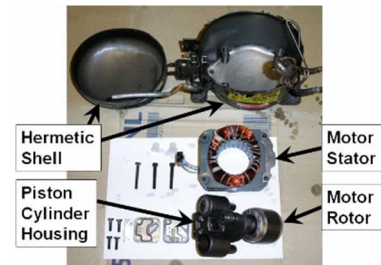


FIGURE 6. Dismantled refrigerator compressor.

The designed motors for the required specification and simulation results are depicted in figure 7 and Table 6 respectively.

TABLE 5. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	120	Watt
Rated Torque	0.38	Nm
Rated Speed	3000	rpm
Outer Diameter	61	mm
Motor Stack Length	33	mm

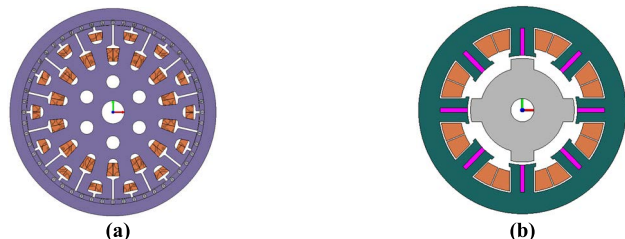


FIGURE 7. (a) SPIM (b) PMFSM.

TABLE 6. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	196.29	167.16	W
Output power	121.7	123.2	W
Efficiency	61.89	73.686	%
Stator core mass	0.1729	0.133	kg
Rotor core mass	0.0589	0.056	kg
Magnet mass	-	0.033	kg
Winding mass	0.376	0.235	kg
Total mass	0.607	0.561	kg

D. AIRCOOLER

The air cooler pulls fresh air from outside and then cools it down. Because of the way it operates, an air cooler offers a better quality of air for our room. Four types of air coolers are (1) Personal Cooler (2) Tower Cooler (3) Window Cooler and (4) Desert Cooler.

In 2022, the market size of the air cooler industry in India is forecasting to amount to around 44.2 billion Indian rupees (INR) [28]. The global air coolers market size was valued at USD 1.2 billion in 2018 and is expected to grow at a CAGR of 10.8% from 2019 to 2025 [29]. Figure 8 shows the dessert cooler and its motor. Technical specifications of the chosen air cooler motor are tabulated in Table 7.



FIGURE 8. Dessert cooler and its motor.

TABLE 7. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	76.5	Watt
Rated Torque	0.562	Nm
Rated Speed	1300	rpm
Outer Diameter	90	mm
Motor Stack Length	36	mm

The designed motors for the required specification and simulation results are depicted in figure 9 and Table 8 respectively.



FIGURE 9. (a) DCM (b) PMFSM.

TABLE 8. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	126.11	107.58	W
Output power	77.23	78.54	W
Efficiency	61.24	72.28	%
Stator core mass	0.169	0.13	kg
Rotor core mass	0.054	0.051	kg
Magnet mass	-	0.03	kg
Winding mass	0.192	0.12	kg
Total mass	0.414	0.331	kg

E. MIXER-GRINDER

The first mixer with an electric motor is thought to be the one invented by American Rufus Eastman in 1885. A mixer grinder is helping in reduce manual work and saving time to allow faster cooking. From pureeing, mixing, grinding, mincing to chopping, the mixer grinder is designed for multiple tasks. According to [30], the sales volume of mixer grinder is anticipated to grow at a CAGR of more than 12% over the next five years in India. Figure 10 shows the mixer-grinder and its motor. Technical specifications of the chosen motor are tabulated in Table 9.



FIGURE 10. Mixer-grinder and its motor.



TABLE 9. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	188	Watt
Rated Torque	0.179	Nm
Rated Speed	10000	rpm
Outer Diameter	90	mm
Motor Stack Length	32	mm

The designed motors for the required specification and simulation results are depicted in figure 11 and Table 10 respectively.

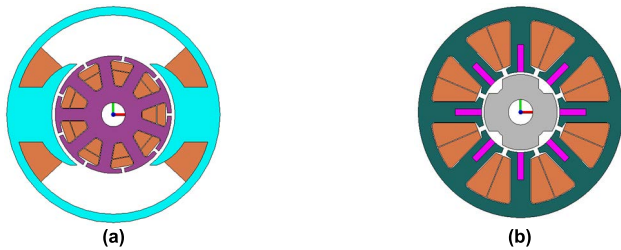


FIGURE 11. (a) DCM (b) PMFSM.

TABLE 10. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	296	261.3	W
Output power	192.46	194.67	W
Efficiency	65.14	74.46	%
Stator core mass	0.312	0.26	kg
Rotor core mass	0.25	0.121	kg
Magnet mass	-	0.24	kg
Winding mass	0.27	0.152	kg
Total mass	0.832	0.773	kg

F. HAND BLENDER

A hand blender helps in the kitchen from blending to pureeing and whipping to kneading. Few types of hand blender are (1) Immersion Blender (2) Chopping Blade (3) Frother (4) Wire Beater, etc. The global hand blender market size was valued at USD 229.2 million in 2018 [31]. The Market is expected to grow at a high CAGR of 7.1% during the forecasting period (2020-2027) [32]. Asia Pacific is expected to witness the fastest growth during forecast years with a CAGR of 9.0% from 2020 to 2027 [33]. Figure 12 shows the hand blender and its motor. Technical specifications of the chosen motor are tabulated in Table 11.

The designed motors for the required specification and simulation results are depicted in Figure 13 and Table 12 respectively.

G. HAND MIXER

Hand mixers are made with two beaters. It can be used to prepare the dough, cake batters, to whip egg whites, cream, or pudding. A mixer does not work to liquidize anything like a hand blender, it only works to combine ingredients. Hand



FIGURE 12. Hand blender and its motor.

TABLE 11. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	250	Watt
Rated Torque	0.136	Nm
Rated Speed	18000	rpm
Outer Diameter	88	mm
Motor Stack Length	30	mm

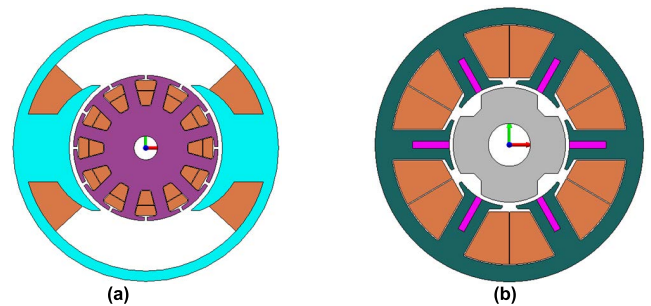


FIGURE 13. (a) DCM (b) PMFSM.

TABLE 12. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	390	357.6	W
Output power	252.3	254.6	W
Efficiency	64.67	71.2	%
Stator core mass	0.32	0.24	kg
Rotor core mass	0.24	0.118	kg
Magnet mass	-	0.22	kg
Winding mass	0.26	0.146	kg
Total mass	0.82	0.724	kg

Mixer Market size was valued at USD 2.33 billion in 2019 and is poised to grow at a CAGR of 6.71% during the forecast period 2020-2025 [34]. Figure 14 shows the hand mixer and its motor. Technical specifications of the chosen motor are tabulated in Table 13.

TABLE 13. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	250	Watt
Rated Torque	0.1	Nm
Rated Speed	25000	rpm
Outer Diameter	85	mm
Motor Stack Length	30	mm



FIGURE 14. Hand blender and its motor.

The designed motors for the required specification and simulation results are depicted in figure 15 and Table 14 respectively.

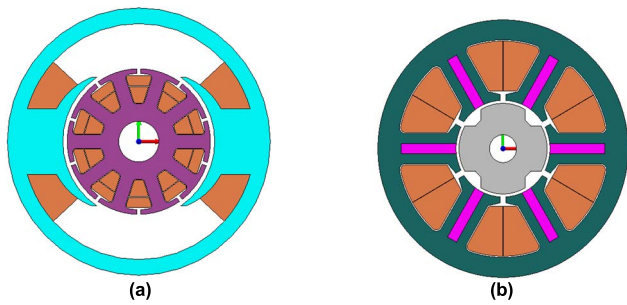


FIGURE 15. (a) DCM (b) PMFSM.

TABLE 14. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	400.5	360	W
Output power	253.1	255.2	W
Efficiency	63.2	70.9	%
Stator core mass	0.31	0.232	kg
Rotor core mass	0.24	0.115	kg
Magnet mass	-	0.22	kg
Winding mass	0.26	0.142	kg
Total mass	0.81	0.709	kg

### H. VACUUM CLEANER

A vacuum cleaner, also known as a Hoover, is a device that causes suction in order to remove debris from floors, upholstery, draperies, and other surfaces. It is an electrically driven with a help of an electric motor. Few types of vacuum cleaners are (1) Canister (2) Drum (3) Hand-held (4) robotic etc.

Household Vacuum Cleaners Market size exceeded USD 20 billion in 2019 and is estimated to grow at a CAGR of over 6.5% between 2020 and 2026 which exceeds USD 30 billion [35]. Figure 16 shows the vacuum cleaner (hand-held) and its motor. Technical specifications of the chosen motor are tabulated in Table 15 [36].

The designed motors for the required specification and simulation results are depicted in figure 17 and Table 16 respectively.



FIGURE 16. Vacuum cleaner and its motor.

TABLE 15. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	300	Watt
Rated Torque	32000	Nm
Rated Speed	0.1	rpm
Outer Diameter	45	mm
Motor Stack Length	22	mm

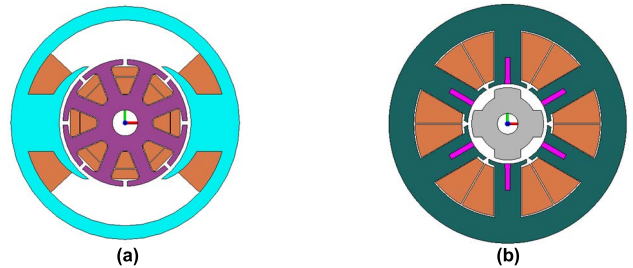


FIGURE 17. (a) DCM (b) PMFSM.

TABLE 16. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	458.1	414.3	W
Output power	303.7	304.5	W
Efficiency	66.31	73.45	%
Stator core mass	0.073	0.016	kg
Rotor core mass	0.05	0.003	kg
Magnet mass	-	0.008	kg
Winding mass	0.092	0.020	kg
Total mass	0.215	0.178	kg

### I. WASHING MACHINE

A washing machine is a home appliance used to wash laundry. Top-loading and front-loading types are mostly dominant washing machines in the commercial market. In India, the market is estimated at INR 9571 crore, with fully automatic machines dominating at 62.6%. Within the fully automatic segment, the top loaders reign with a 63.43% revenue share.

Further, the market size is expected to reach USD 5.34 billion by 2022 [37]. Global Residential washing machine market was valued at USD 36,648 million in 2016, and is projected to reach USD 53,193 million by 2023, growing at a CAGR of 5.5% from 2017 to 2023 [38]. Figure 18 shows the front loading and its motor. Technical specifications of the chosen motor are tabulated in Table 17. The designed

motors for the required specification and simulation results are depicted in figure 19 and Table 18 respectively.



FIGURE 18. Washing machine and its motor.

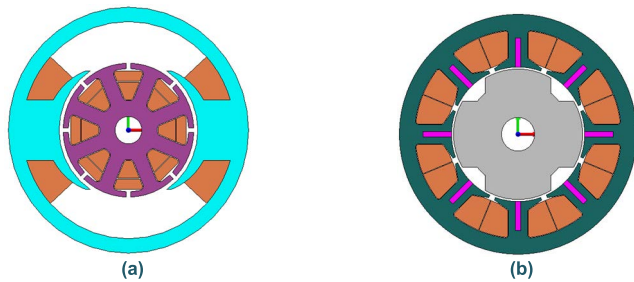


FIGURE 19. (a) DCM (b) PMFSM.

TABLE 17. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	550	Watt
Rated Torque	3.5	Nm
Rated Speed	1500	rpm
Outer Diameter	122	mm
Motor Stack Length	46	mm

**J. DISHWASHER**

A dishwasher is a machine used to clean dishware and cutlery automatically. India dishwasher market to cross USD 90 million by 2026 and is expected to grow at a CAGR of over 12% during the forecast period [39].

The global dishwasher market size was valued at USD 6.29 billion in 2018 and is expected to register the CAGR of over 8% from 2019 to 2025 [40]. According to [41], the dishwasher market and it is poised to grow by USD 1.34 billion during 2020-2024, progressing at a CAGR of over 1% during the forecast period. Figure 20 shows the dishwasher and its motor. Technical specifications of the chosen motor are tabulated in Table 19.

The designed motors for the required specification and simulation results are depicted in figure 21 and Table 20 respectively.

**K. DOMESTIC JUICERS**

A juicer, also known as a juice extractor, is a tool used to extract juice from fruits, herbs, leafy greens, and other



FIGURE 20. Dishwasher and its motor.

TABLE 18. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	818	669	W
Output power	557	563.6	W
Efficiency	68.1	84.2	%
Stator core mass	2.010	1.910	kg
Rotor core mass	0.825	0.584	kg
Magnet mass	-	0.425	kg
Winding mass	1.080	0.728	kg
Total mass	3.915	3.647	kg

TABLE 19. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	90	Watt
Rated Torque	0.43	Nm
Rated Speed	2000	rpm
Outer Diameter	94	mm
Motor Stack Length	31	mm

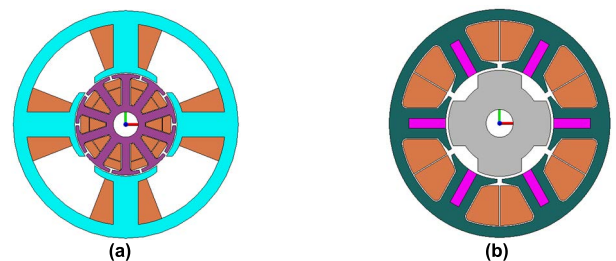


FIGURE 21. (a) DCM (b) FSM.

TABLE 20. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	147	131	W
Output power	92.8	93.4	W
Efficiency	63.21	71.3	%
Stator core mass	0.172	0.14	kg
Rotor core mass	0.072	0.055	kg
Magnet mass	-	0.033	kg
Winding mass	0.18	0.14	kg
Total mass	0.424	0.368	kg

types of vegetables [42]. Growing demand for fruit juices among consumers is expected to create new opportunities in the market. Juicer market will witness a growth rate

of 7.65% for the forecast period of 2020 to 2027. [43]. According to [44], the global juicer market is expected to post a CAGR of almost 8% during the period 2019-2023. Figure 22 shows a commercial domestic juicer and its motor. Technical specifications of the chosen motor are tabulated in Table 21.



FIGURE 22. Domestic juicer and its motor.

TABLE 21. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	750	Watt
Rated Torque	0.955	Nm
Rated Speed	7500	rpm
Outer Diameter	87	mm
Motor Stack Length	42	mm

The designed motors for the required specification and simulation results are depicted in figure 23 and Table 22 respectively.

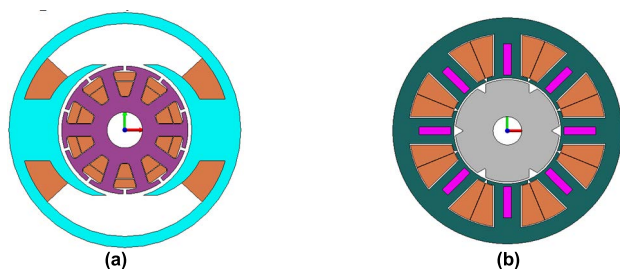


FIGURE 23. (a) DCM (b) PMFSM.

TABLE 22. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	1114.3	956	W
Output power	753.3	754.2	W
Efficiency	67.6	78.9	%
Stator core mass	0.77	0.63	kg
Rotor core mass	0.31	0.18	kg
Magnet mass	-	0.12	kg
Winding mass	0.2	0.16	kg
Total mass	1.28	1.09	kg

L. COFFEE MACHINE

A coffee machine is a cooking appliance used to brew coffee. This is also called automatic drip-brew [45]. Indian coffee machine market is projected to grow at a CAGR of over 16%

by 2023, because of rising coffee culture and increasing dual household income across the country [46]. The global coffee machines market is expected to grow from USD 5.11 billion in 2020 to USD 5.45 billion in 2021 at a CAGR of 6.7%. The market is expected to reach USD 6.36 billion in 2025 at a CAGR of 4% [47]. Figure 24 shows a coffee machine and its motor. Technical specifications of the chosen motor are tabulated in Table 23.



FIGURE 24. Coffee machine and its motor.

TABLE 23. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	750	Watt
Rated Torque	5.12	Nm
Rated Speed	1400	rpm
Rotor Outer Diameter	86	mm
Motor Stack Length	39	mm

The designed motors for the required specification and simulation results are depicted in figure 25 and Table 24 respectively.

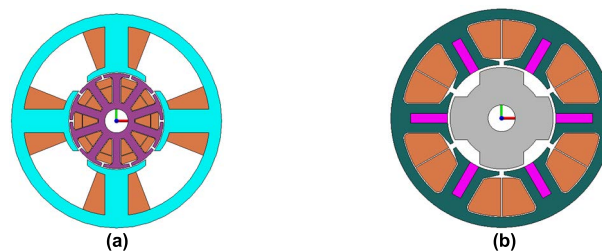


FIGURE 25. (a) DCM (b) PMFSM.

TABLE 24. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	1026	931	W
Output power	752.8	756.1	W
Efficiency	73.4	81.2	%
Stator core mass	0.91	0.83	kg
Rotor core mass	0.39	0.22	kg
Magnet mass	-	0.17	kg
Winding mass	0.36	0.31	kg
Total mass	1.66	1.53	kg

M. HAIRDRYER

A hairdryer, also known as a blow dryer, is an electromechanical device used to dry and style hair [48]. India



female grooming market stood at USD 226.95 million in 2020 and is projected to grow at a CAGR of over 21.16% in the next five years. India male grooming market stood at USD 208.22 million in 2020 and is projected to grow at a CAGR of over 20.97% to cross USD 590.54 million by 2026 [49].

The global hairdryer market size was valued at USD 7.09 billion in 2018 and is projected to expand at a CAGR of 5.1% from 2019 to 2025 [50]. Further [51], the hair dryer market size is expected to grow by USD 1.03 billion and record a CAGR of 3% during 2020-2024. Figure 26 shows a domestic hair dryer and its motor. Technical specifications of the chosen motor are tabulated in Table 25.



FIGURE 26. Hairdryer and its motor.

TABLE 25. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	25	Watt
Rated Torque	0.024	Nm
Rated Speed	10000	rpm
Rotor Outer Diameter	70	mm
Motor Stack Length	21	mm

The designed motors for the required specification and simulation results are depicted in figure 27 and Table 26 respectively.

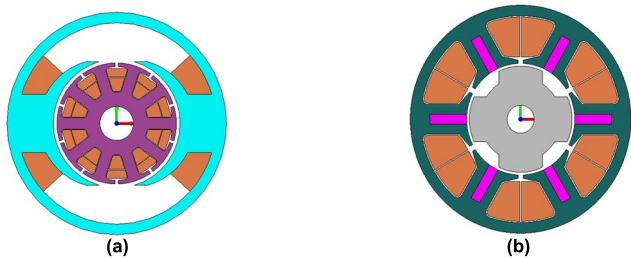


FIGURE 27. (a) DCM (b) PMFSM.

**N. AIR CONDITIONING**

Air conditioning is the process of removing heat and controlling the humidity of the air within a building. Indian air conditioners market stood at over USD 4.3 billion in 2017 and

TABLE 26. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	46.2	40.3	W
Output power	27.6	28.3	W
Efficiency	59.7	70.22	%
Stator core mass	0.13	0.11	kg
Rotor core mass	0.054	0.032	kg
Magnet mass	-	0.027	kg
Winding mass	0.13	0.1	kg
Total mass	0.314	0.269	kg

is projected to grow at a CAGR of more than 17%, to surpass USD 11 billion by 2023 [52]. The global air conditioning systems market size was USD 102.02 billion in 2018 and is expected to register a CAGR of 9.9% from 2019 to 2025 [53]. There are 3 major parts of the AC system where electric motors are used. They are (1) Compressor (2) condenser fan and (3) Outdoor fan.

1) AC COMPRESSOR

Figure 28 shows an AC compressor and its motor. Technical specifications of the chosen motor are tabulated in Table 27.



FIGURE 28. AC compressor and its motor.

TABLE 27. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	1600	Watt
Rated Torque	2.04	Nm
Rated Speed	7500	rpm
Outer Diameter	183	mm
Motor Stack Length	98	mm

The designed motors for the required specification and simulation results are depicted in figure 29 and Table 28 respectively.

2) AC CONDENSER FAN

Figure 30 shows an AC condenser fan and its motor. Technical specifications of the chosen motor are tabulated in Table 29. The designed motors for the required specification and simulation results are depicted in figure 31 and Table 30 respectively.

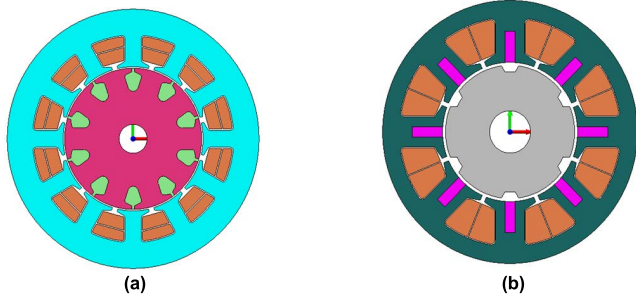


FIGURE 29. (a) IM (b) PMFSM.

TABLE 28. Performance comparison.

Parameter	IM	PMFSM	Unit
Input power	2241	1935	W
Output power	1609	1618	W
Efficiency	71.8	83.6	%
Stator core mass	2.1	2.01	kg
Rotor core mass	1.43	0.61	kg
Magnet mass	-	0.41	kg
Winding mass	0.88	0.81	kg
Total mass	4.41	3.84	kg

TABLE 29. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	42	Watt
Rated Torque	0.297	Nm
Rated Speed	1350	rpm
Outer Diameter	97	mm
Motor Stack Length	70	mm



FIGURE 30. AC condenser fan and its motor.

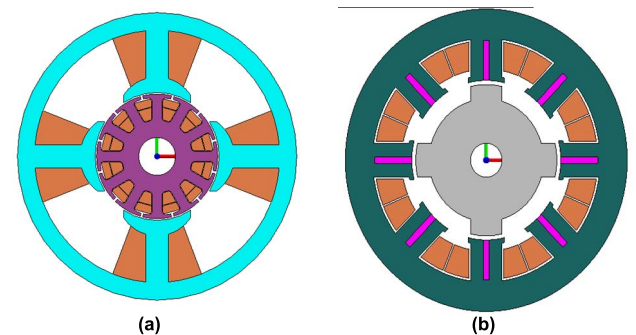


FIGURE 31. (a) DCM (b) PMFSM.

### 3) AC OUTDOOR FAN

Figure 32 shows an AC outdoor fan and its motor. Technical specifications of the chosen motor are tabulated in Table 31.

TABLE 30. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	77	65.1	W
Output power	44.8	45.7	W
Efficiency	58.23	70.2	%
Stator core mass	0.14	0.1	kg
Rotor core mass	0.037	0.032	kg
Magnet mass	-	0.023	kg
Winding mass	0.13	0.1	kg
Total mass	0.307	0.255	kg



FIGURE 32. AC outdoor fan and its motor.

The designed motors for the required specification and simulation results are depicted in figure 33 and Table 32 respectively.

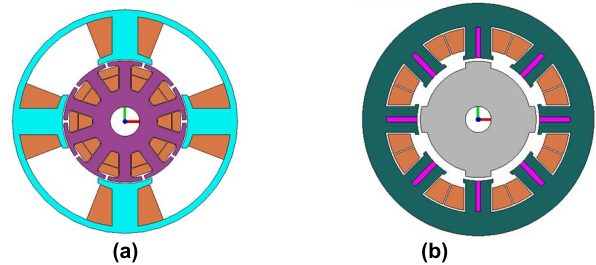


FIGURE 33. (A) DCM (B) PMFSM.

TABLE 31. Technical specifications.

Parameter	Specifications	Unit
Rated Voltage	48	Volt
Rated Power	53	Watt
Rated Torque	0.563	Nm
Rated Speed	900	rpm
Outer Diameter	100	mm
Motor Stack Length	74	mm

TABLE 32. Performance comparison.

Parameter	DCM	PMFSM	Unit
Input power	89	80	W
Output power	54.4	57.2	W
Efficiency	61.1	71.3	%
Stator core mass	0.18	0.15	kg
Rotor core mass	0.04	0.038	kg
Magnet mass	-	0.025	kg
Winding mass	0.16	0.14	kg
Total mass	0.38	0.353	kg

**TABLE 33. Power consumption, efficiency, and mass comparisons of the chosen applications.**

Sl. No	Applications	Power Consumption (Watt)		Efficiency (%)		Total Mass (kg)		Remarks (PMFSM in comparison with the existing technology)
		DCM	PMFSM	DCM	PMFSM	DCM	PMFSM	
1	Water Purifier	19.2	17.1	63.64	72.19	0.781	0.713	<ul style="list-style-type: none"> <li>• 12.28% reduced power consumption</li> <li>• 8.55% more efficient</li> <li>• 9.54% reduced mass</li> </ul>
2	Ceiling fan	52 (SPIM)	31	43.1	76.13	2.195	1.017	<ul style="list-style-type: none"> <li>• 67.7% reduced power consumption</li> <li>• 33% more efficient</li> <li>• 115% reduced mass</li> </ul>
3	Refrigerator	196.29 (SPIM)	167.16	61.89	73.686	0.607	0.561	<ul style="list-style-type: none"> <li>• 17.4% reduced power consumption</li> <li>• 11.8% more efficient</li> <li>• 8.2% reduced mass</li> </ul>
4	Air cooler	126.11	107.58	61.24	72.28	0.414	0.331	<ul style="list-style-type: none"> <li>• 17.2% reduced power consumption</li> <li>• 11% more efficient</li> <li>• 25% reduced mass</li> </ul>
5	Mixer - grinder	296	261.3	65.14	74.46	0.832	0.773	<ul style="list-style-type: none"> <li>• 13.3% reduced power consumption</li> <li>• 9.32% more efficient</li> <li>• 7.6% reduced mass</li> </ul>
6	Hand blender	390	357.6	64.67	71.2	0.82	0.724	<ul style="list-style-type: none"> <li>• 9% reduced power consumption</li> <li>• 6.5% more efficient</li> <li>• 13.3% reduced mass</li> </ul>
7	Hand mixer	400.5	360	63.2	70.9	0.81	0.709	<ul style="list-style-type: none"> <li>• 11.25% reduced power consumption</li> <li>• 7.7% more efficient</li> <li>• 14.24% reduced mass</li> </ul>
8	Vacuum cleaner	458.1	414.3	66.31	73.45	0.215	0.178	<ul style="list-style-type: none"> <li>• 10.6% reduced power consumption</li> <li>• 7.14% more efficient</li> <li>• 20.8% reduced mass</li> </ul>
9	Washing machine	818	669	68.1	84.2	3.915	3.647	<ul style="list-style-type: none"> <li>• 22% reduced power consumption</li> <li>• 16.1% more efficient</li> <li>• 7.3% reduced mass</li> </ul>
10	Dishwashers	147	131	63.21	71.3	0.424	0.368	<ul style="list-style-type: none"> <li>• 12.2% reduced power consumption</li> <li>• 8.1% more efficient</li> <li>• 15.2% reduced mass</li> </ul>
11	Domestic juicer	1114.3	956	67.6	78.9	1.28	1.09	<ul style="list-style-type: none"> <li>• 16.5% reduced power consumption</li> <li>• 11.3% more efficient</li> <li>• 17.4% reduced mass</li> </ul>
12	Coffee machine	1026	931	73.4	81.2	1.66	1.53	<ul style="list-style-type: none"> <li>• 10.2% reduced power consumption</li> <li>• 7.8% more efficient</li> <li>• 8.5% reduced mass</li> </ul>
13	HairDryer	46.2	40.3	59.7	70.22	0.314	0.269	<ul style="list-style-type: none"> <li>• 14.6% reduced power consumption</li> <li>• 10.52% more efficient</li> <li>• 16.7% reduced mass</li> </ul>
14	AC compressor	2241 (IM)	1935	71.8	83.6	4.41	3.84	<ul style="list-style-type: none"> <li>• 15.8% reduced power consumption</li> <li>• 11.8% more efficient</li> <li>• 14.8% reduced mass</li> </ul>
15	AC condenser fan	77	65.1	58.23	70.2	0.307	0.255	<ul style="list-style-type: none"> <li>• 18.3% reduced power consumption</li> <li>• 12% more efficient</li> <li>• 20.4% reduced mass</li> </ul>
16	AC outdoor fan	89	80	61.1	71.3	0.38	0.353	<ul style="list-style-type: none"> <li>• 11.25% reduced power consumption</li> <li>• 10.2% more efficient</li> <li>• 7.6% reduced mass</li> </ul>

Note: IM – Induction Motor, SPIM - Single Phase Induction Motor

### III. CONCLUSION

Energy-efficient domestic appliances are going to rule the global market in near future. 48-Volt dc systems pave

the way to manufacture various smart domestic appliances in a multidimensional approach. Since the market value is in billion, the manufacturing cost of each product

will have a huge impact on the customer point of view.

Conventional commutator motors lag in efficiency and are more bulky. The proposed PMFSM, is having at least 10% more efficiency with a significant overall mass reduction compared to the existing motors as evident from the Table 33. This shows new insights towards the proposed FSM drive system to explore more towards the commercial use. Smart appliances demand sophisticated control as well as compact sizing. Industry 4.0 which includes (i) 3D printing, (ii) Artificial intelligence (AI) and (iii) Internet-of-things (IOT) plays a vital part in implementing those smart appliances. Further, Society 5.0 will emerge in near future, which focusses on environmental issues at large. Altogether, the proposed technology with no doubt will emerge as a smart contender in the domestic appliances.

Apart from the discussed applications, PMFSM may find its foothold in (a) pumps (b) compressors and (c) automotive applications like wiper systems, water pumps, HVAC, etc. in near future because of its simple magnetic structure and control circuit.

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**NATESAN CHOKKALINGAM LENIN** (Senior Member, IEEE) received the Ph.D. degree from Anna University, Chennai, India, in 2012. He is having 20 years of teaching experience. Currently, he is a Professor and the Director of the Electric Vehicles—Incubation, Testing and Research Centre with the Vellore Institute of Technology, Chennai. He is closely working with many industries and government agencies for the development of high performance electric motor drives. He has

published more than 60 international journals and international conference papers. He has four patents. His research interests include finite element analysis, advanced electromagnetics, design of low cost, high performance electrical machines, and its controller for automotive and domestic applications. He is the Editor and an Associate Editor of *The Global Electrical Engineers* and *International Journal of Electrical and Computer Engineering*, respectively. He is the Editorial Member of *Majlesi Journal of Energy Management*.

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