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RESEARCH ARTICLE

A Novel Brushless Wound Rotor Synchronous Machine Utilizing Inherent Sub-Harmonic Component

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ABSTRACT Permanent magnet synchronous machines (PMSMs) contain a simple structure, high efficiency, and simple control. However, their cost has increased significantly due to the increase in the price of permanent magnets. Wound rotor synchronous machines (WRSMs) can be used as an alternative to PMSMs. In WRSMs, there is no need for permanent magnets as the rotors of these machines are electromagnets. However, there is the sparking issue which consequently requires regular maintenance of slip rings and carbon brushes. The research focus in recent times is to eliminate the brushes and slip rings in the conventional WRSMs. This manuscript presents a novel brushless wound rotor synchronous machine (BL-WRSM) utilizing an inherent subharmonic component (SHC). The proposed design achieves a brushless function by utilizing the inherent SHC of the stator magnetomotive force (MMF) inherently available in the air gap. As compared to the existing distributed winding BL-WRSM, the proposed BL-WRSM does not involve any extra circuitry at the stator side, additional inverter, or special stator winding arrangements. Utilizing SHC provides benefits such as reduced torque ripple and symmetrical flux distribution as compared to existing brushless machines. There are two distinct windings present on the rotor in the suggested BL-WRSM. These are field winding (FW) and harmonic winding (HW). A rectifier connects these windings in parallel with one another. The SHC of stator MMF generates an AC voltage in HW. This AC voltage is converted to DC by a rectifier, which powers the rotor FW. Validation of brushless operation of the suggested 8-pole, 12-slot machine is conducted through a 2-dimensional finite element analysis with the help of JMAG software. The suggested topology results in desired torque at rated speed with low torque ripples.

INDEX TERMS Brushless operation, finite element analysis, inherent sub-harmonic component, wound rotor synchronous machine.

NOMENCLATURE

AC	Alternating current.
BL-WRSM	Brushless wound rotor synchronous machine.
C-WRSM	Conventional wound rotor synchronous machine.
DC	Direct current.
FC	Fundamental component.
FEA	Finite element analysis.
FEM	Finite element method.
FW	Field winding.
HW	Harmonic winding.
MMF	Magneto motive force.
PM	Permanent magnet.
PMSMs	Permanent magnet synchronous machines.

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SHC	Subharmonic component.
SW	Stator winding.
THC	Third harmonic component.
WRSMS	Wound rotor synchronous machines.

I. INTRODUCTION

Electrical machines play a very important role in industry as well as in our daily lives. These are used in renewable energy integration [1], [2], household appliances [3], electrical vehicles [4], agriculture [5], and variable speed applications [6]. Among electrical machines, synchronous machines constitute an important class of machines where rotors move at synchronous speed. The major types of commonly available synchronous machines based upon rotor type are permanent magnetic synchronous machines containing a permanent magnetic rotor and wound rotor synchronous machines having an electromagnetic rotor with carbon brushes and slip rings. In PMSM, there is no need for carbon brushes and slip rings because its rotor is a permanent magnet (PM) [7]. However, PMSMs are expensive and undergo demagnetization problems during the fault conditions causing decreased efficiency in the field weakening region [8], [9]. Due to these issues, research is going on to develop synchronous motors that either have less reliance or absolutely no reliance on PMs. Motors with hybrid excitation systems have partial reliance on PMs whereas WRSMs are free of any PM [10], [11]. To achieve brushless excitement in WRSMs, several techniques have been employed [12]. Steam and hydel-based alternators use an external brushless exciter for rotor field excitation. However, economic factors limit the usage of these exciters in small synchronous machines [13].

To generate rotor flux in conventional or normal WRSM, direct current (DC) is applied to rotor field winding (FW) with the help of carbon brushes and slip rings. This assembly with brushes and slip rings for synchronous machines is not highly suitable because it produces sparks, adds losses, and requires maintenance [14].

Researchers are working to obtain brushless excitation systems in synchronous machines. Stator magneto motive force (MMF) containing a third harmonic component (THC) was proposed for brushless operation in [15]. Two separate inverters were used, one for fundamental current, while the other one was for THC delivered to stator windings (SWs). Due to the third harmonic present in stator MMF, alternating current (AC) voltage is generated in harmonic winding (HW), which is converted to DC using a rectifier. This DC is supplied to rotor FW to obtain brushless working of the suggested machine. However, the use of an extra inverter is the disadvantage of this design.

Reference [16] analyzes a synchronous machine as a generator with an extra HW present on the stator. DC excitation is given to stator HW to establish THC in stator MMF. Rotor HW experiences AC voltage due to THC presence in stator MMF. After rectification of HW voltage, DC is provided to FW of the synchronous machine to achieve brushless operation. However, it is done only for synchronous generators and not for motors. The requirement of two SWs is its major drawback.

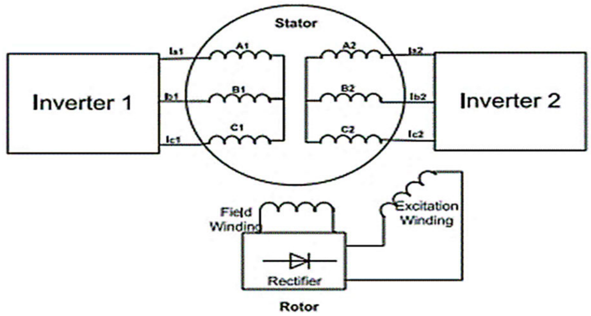


FIGURE 1. BL-WRSM with dual inverter topology.

In [17], a brushless wound rotor synchronous machine (BL-WRSM) design is presented in which by generating a controllable zero sequence current, THC was created in BL-WRSM. To generate zero sequence current, thyristor switches are used in parallel with the SW of the synchronous machine. These switches are switched on during positive and negative half cycles of current passing through SW. A stator MMF with THC created from a controllable current with zero sequence is then coupled to the HW of the rotor which induces AC voltages in HW. A rectifier is connected to the rotor boundary to rectify the AC voltages of HW. DC power is then given to rotor FW. The disadvantage of the suggested model is the requirement of switches and control circuitry, needed to switch during each cycle to generate zero-sequence current.

In [18], a brushless topology has been discussed for the BL-WRSM. In this topology, a stator MMF that has a subharmonic component (SHC) is used for the brushless function of a synchronous machine. Dividing 3-phase SWs into two sets of windings placed spatially on the stator provides SHC in stator MMF. The HW establishes an AC voltage due to this SHC. To get brushless operation, rotor FW receives DC after HW's AC voltage is converted to DC using a rectifier. However, the proposed model utilizes two inverters for this brushless operation which increases the dimensions of the brushless excitation system. The schematic diagram of BL-WRSM with dual inverter topology is shown in Fig. 1.

In [19], the proposed machine achieves brushless working by the usage of SHC found in stator MMF. However, the stator side of windings is divided into two portions, which results in an asymmetrical stator slot fill factor and asymmetrical flux distribution in the stator of the suggested machine.

In [20], two armature windings are present on the stator, which allows the suggested machine to run brushless. Two inverters are required to supply these two armature windings. Since this topology uses two inverters and two stator armature windings, the overall cost of the machine increases, and stator armature losses also increase. Moreover, due to two inverters, losses in inverters will also increase in comparison to that technique in which only one inverter is used.

TABLE 1. Pros and cons of existing machine topologies.

References	Year	Used Topology for BL-WRSM	Advantages	Limitations
[18]	2015	Two sets of spatially placed windings on the stator to provide SHC.	No brushes are required.	Two inverters for this brushless operation increase the dimensions of the brushless excitation system.
[19]	2018	Division of SWs in two portions to provide SHC.	SHC generation using special SW arrangement.	Asymmetrical stator slot fill factor and asymmetrical flux distribution in the stator.
[28]	2020	Time harmonic generation in MMF.	Brushless working of the machine.	Higher cost due to two inverters.
[27]	2021	Special rotor structure to generate reluctance torque.	Utilization of reluctance torque to get starting torque.	More torque ripples.
[20]	2021	Two armature windings on the stator.	Brushless functioning.	• Increased losses in two windings. • Increased cost due to two inverters supplying two armature windings.
[21]	2022	Hysteresis controller-based topology to generate the third harmonic in stator MMF.	Brushless operation is achieved by employing a single inverter.	• Cost of additional controller • The possibility of other harmonics components resulting in more armature losses.
[25]	2022	SHC-based topology with PM.	Higher starting torque due to PM.	• Higher cost due to two inverters and PM.
[26]	2022	Dual mode topology.	The machine operates in two modes (brushless mode and with brushes).	Higher cost due to two inverters.
[22]	2023	Five and higher phase brushless synchronous machine topology.	The machine remains in working condition despite one phase failure.	More switches are required to generate five or higher phase AC supply resulting in more switching loss.
[23]	2023	SHC-based topology.	Brushless operation.	• Increased size due to outer rotor. • More ripples in spin mode.
[24]	2023	SHC-based topology with two stators.	Brushless operation.	The machine has two stators which increase the size and cost of the machine.

In [21], a hysteresis controller is used to give the third harmonic of MMF to stator armature winding which then induces AC voltages in HW of the rotor. After the rectification of AC voltages, DC is given to the FW of the rotor. However, the drawback of the suggested machine is that an additional controller must be used to provide a third harmonic to SW which would result in higher costs. There is a possibility that other harmonics components to be produced in the armature winding due to this controller and hence armature losses will increase.

Five and higher phase brushless synchronous machines are presented in [22]. The advantage of this machine is that if any one phase goes out of order the machine remains in working condition. However, the disadvantage is that for the five-phase, there is a need for 10 switches to convert DC into 5-phase AC and similarly for the 6 phase there is a need for 12 switches to convert DC supply into 6-phase AC. Hence, significant power loss occurs in these switches.

In [23], SHC is used to obtain brushless operation of the machine. However, the suggested machine has an outer rotor increasing the size of the machine. Moreover, torque ripples in the spin mode of the suggested machine are also high.

In [24], SHC is used for the operation of the machine without brushes. However, the suggested machine has two stators and one rotor increasing the size and cost of the machine.

In [25], SHC is used for the operation of the machine without brushes. However, the proposed machine uses two inverters: one for the fundamental component (FC) of stator MMF and the second inverter to provide SHC. In this topology, PM is also used to get significant starting torque. Due to these two inverters and PM, the cost of the machine is high.

In [26], proposed machine works as a dual-mode topology. Armature winding containing two sets is present on the stator. Two inverters are used to produce subharmonics and to change the operation of the machine from mode-1 to mode-2, five switches are required which increases machine losses.

In [27], a reluctance torque is used to get a significant starting torque and improvement in average torque without using permanent magnetic material.

In [28], the synchronous machine's brushless functioning is accomplished by regulating the time harmonic MMF. But this topology also requires two inverters, which raises the cost.

In [29], a BL-WRSM with a wye-delta winding architecture is suggested. However, a single inverter is required to provide THC in stator MMF to obtain the brushless function. AC voltage is produced in HW due to this harmonic component. By changing this voltage in DC with the help of a rectifier, DC is given to rotor FW.

In [30], the stator has two windings namely exciter winding and the 3-phase armature winding for brushless excitation. The diode rectifier and two windings, the field and harmonic windings, are mounted on the rotor. The single exciter winding is coupled in series with the armature winding of 3 phases. A single inverter is feeding supply to the SW. The requirement of two SWs is a major drawback of this suggested machine.

In [31], SHC is used to get brushless operation. This is achieved by making two sets of windings on the stator and using a thyristor switch to change the modes as the suggested machine is analyzed for dual mode.

Table 1 presents a clearer discussion presenting the pros and cons of each topology.

The existing brushless excitation schemes published in literature use different techniques to generate harmonics. Some techniques use two SWs, and some deploy dual inverters. Both these techniques increase the cost of machines which is a major limitation of these designs.

To reduce the cost, this research presents a novel design with the following contributions.

- It uses a single SW and a single inverter to ensure brushless functioning which reduces its cost.
- The novel BL-WRSM deploys concentrated winding, using an inherent sub-harmonic component which is present in the stator MMF.
- In the proposed design, the rotor has HW and FW. The number of poles of HW and poles of SHC are the same.
- AC voltage is generated in HW due to SHC present in stator MMF. After rectification, DC power is given to FW present on the rotor to get brushless operation of the suggested machine.

The rest of the manuscript is arranged as follows. Section II presents the topology and operating principle of the proposed machine. Analytical performance analysis of the proposed machine using 2-D finite element analysis (FEA) is presented in Section III and Section IV concludes the paper.

II. PROPOSED BRUSHLESS TOPOLOGY, MACHINE CONFIGURATION AND OPERATION PRINCIPLE

A. PROPOSED BRUSHLESS TOPOLOGY

The brushless topology proposed is illustrated in Fig. 2. Utilizing the inherent SHC of stator MMF for brushless operation, SW of the suggested BL-WRSM is a simple 3-phase concentrated winding which is powered by a balanced 3-phase supply via a 3-phase inverter. This SW is also known as 3-phase armature windings. A balanced 3-phase supply can be taken from a 3-phase inverter which converts DC into 3-phase balanced AC. A bridge rectifier is used to connect FW and HW on the rotor in parallel. The SHC of stator MMF has the same number of poles as the HW.

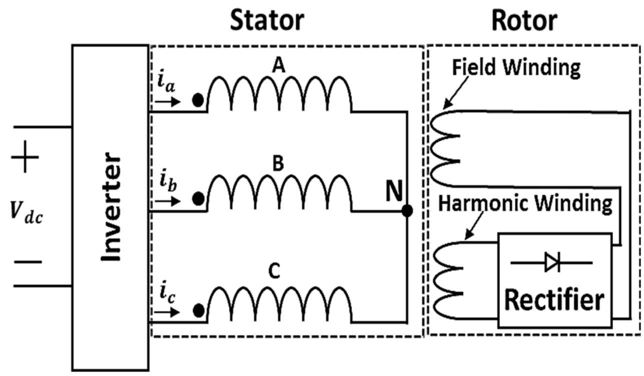


FIGURE 2. Illustration of the proposed brushless topology.

This SHC generates a magnetic field that is rotating in the air gap, inducing AC voltage in the HW. The rectifier rectifies this induced voltage, and DC is supplied to the rotor FW. To produce torque in the suggested machine, the number of poles in the FW and the SW are kept the same.

B. MACHINE CONFIGURATION

An 8-pole, 12-slot BL-WRSM is designed in 2-D to validate the suggested topology. The arrangement of the suggested BL-WRSM is depicted in Fig. 3, wherein the stator comprises a single-layer winding.

The suggested 2-D model of the machine is illustrated in Fig. 3, and Table 2 provides information about the specifications of the proposed BL-WRSM. The rotor is located on the inside side of this machine whereas the stator is at the outer side of the suggested machine. The stator as well as rotor winding configurations of the suggested machine are shown in Fig. 4.

This SW arrangement results in two dominant components, namely the FC with harmonic order 1 and inherent SHC with harmonic order 0.5, as illustrated in Fig. 6. Due to the 0.5 harmonic order of SHC, HW is present in half slots of the rotor as seen in Fig. 3.

C. OPERATING PRINCIPLE

In contrast to the existing BL-WRSM model employing dual inverters to achieve brushless operation, the proposed BL-WRSM model merely requires a single 3-phase inverter. In this proposed configuration, there is no need for additional winding on the stator. Similarly, no extra inverter is required to produce the SHC in stator MMF.

The working principle of the suggested model is based on the inherent SHC of stator MMF achieved by powering

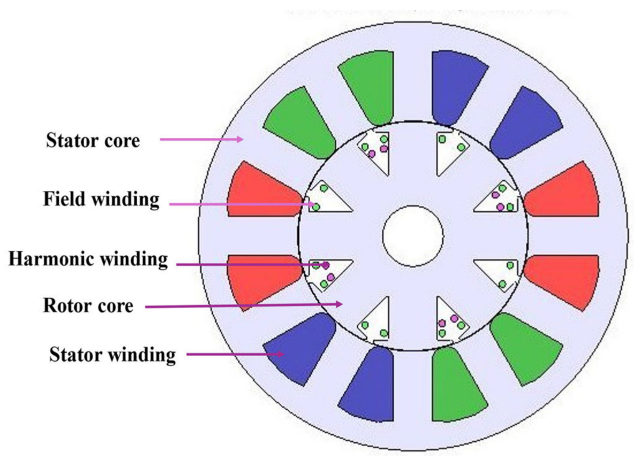


FIGURE 3. 2-D model of proposed 8-pole, 12-slot, BL-WRSM.

TABLE 2. Machine design parameters.

Parameter	Units	Proposed BL-WRSM
Rated power	W	746
Rated speed	rpm	900
Rated Frequency	Hz	60
Number of phases	-	3
Stator outer diameter	mm	177
Stator inner diameter	mm	95
Air gap length	mm	0.5
Stack length	mm	80
Shaft diameter	mm	25
Number of poles	-	8
Number of stator slots	-	12
Stator winding turns per phase	-	240
Field winding turns	-	224
Harmonic winding turns	-	32
Winding material	-	Copper
Core material	-	50H1300

3-phase SW with a balanced 3-phase AC supply. Both components, fundamental and inherently SHC, are present in the stator MMF.

The SHC of stator MMF produces a magnetic field that is in rotating condition within the air gap, inducing AC voltage in the HW of the rotor. This produced voltage within the rotor's HW is subsequently rectified using a rectifier positioned on the rotor. From the rectifier, DC power is taken and given to the FW of the rotor without brushes. The FW generates the main magnetic field within the rotor. The working principle in a brief form of proposed BL-WRSM is depicted in Fig. 5. The 3-phase currents given to the SW can be mathematically expressed as:

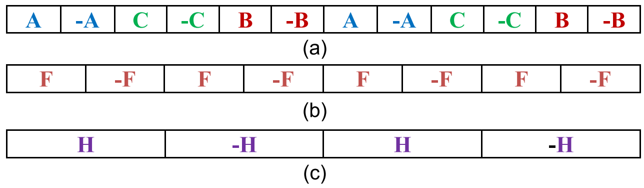


FIGURE 4. (a). Stator winding arrangement. (b). Field winding arrangement. (c). Harmonic winding arrangement.

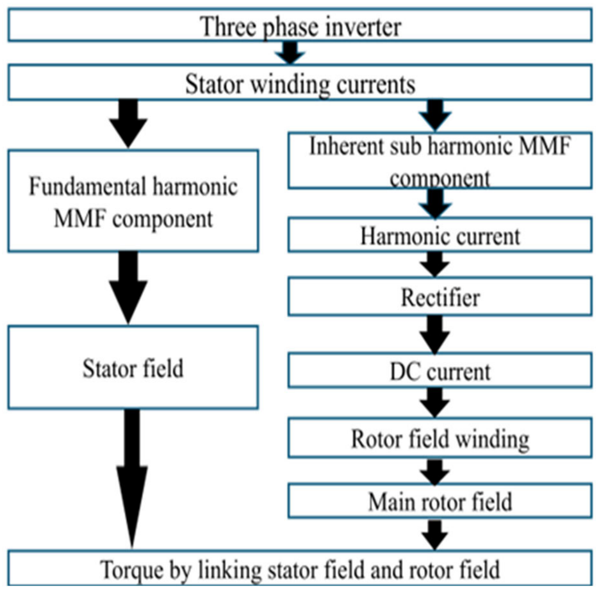


FIGURE 5. Working principle of the proposed machine.

$$i_a = I_m sin\omega_e t \quad (1)$$

$$i_b = I_m sin(\omega_e t - 2\pi/3) \quad (2)$$

$$i_c = I_m sin(\omega_e t + 2\pi/3) \quad (3)$$

Here t, ω_e and I_m represent time, angular frequency, and maximum amplitude of current provided by the inverter respectively.

The fundamental MMF component is moving at a speed of 900 rpm and the SHC of stator MMF is revolving at 1800 rpm because the SHC is of 0.5 order. Since SHC rotates at 1800 rpm, which is twice as fast as the FC of stator MMF. Due to the double speed of SHC, it can produce emf in the rotor because the rotor moves in synchronization with the FC of stator MMF. To obtain this generation, there is a need for some special winding known as HW.

Fig. 6 displays the winding harmonics of the proposed machine. There are two significant harmonic components of stator MMF: (1) 8-pole of fundamental harmonic component, (2) 4-pole of sub-harmonic component. This second component of stator MMF makes AC voltage in HW. This AC

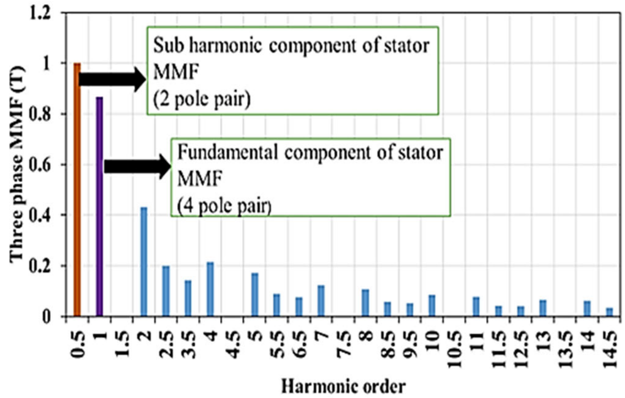


FIGURE 6. MMF of 8-pole and 12-slots proposed BL-WRSM.

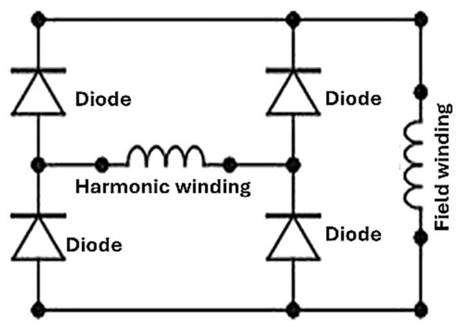


FIGURE 7. Schematic diagram of rotor harmonic winding, rectifier and field winding.

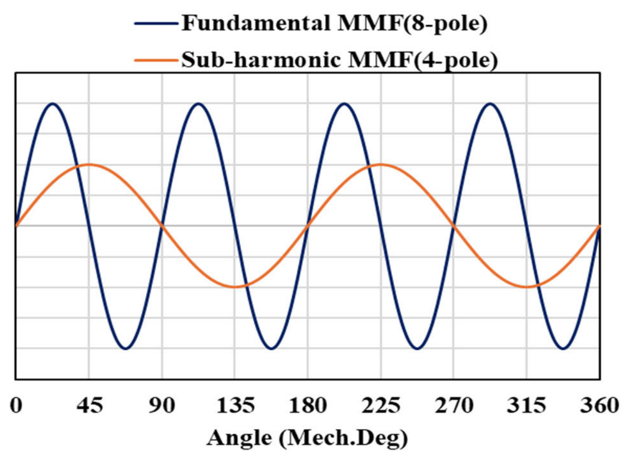


FIGURE 8. Dominant MMF components present in the air gap of the proposed machine.

voltage induced in HW is rectified using a rectifier to get DC and DC is provided to FW to achieve brushless operation. Finally, the interaction between the main rotor field and the main stator field allows the suggested BL-WRSM to work and produce torque in the rotor. Fig. 7. shows a schematic diagram of the rotor HW, rectifier, and FW of the proposed BL-WRSM.

The graphical presentation of harmonic components present in stator MMF can be viewed in Fig. 8. It is obvious from the figure that there are 8 poles of this FC having frequency, ω_e, in contrast to the 4 poles of the other SHC

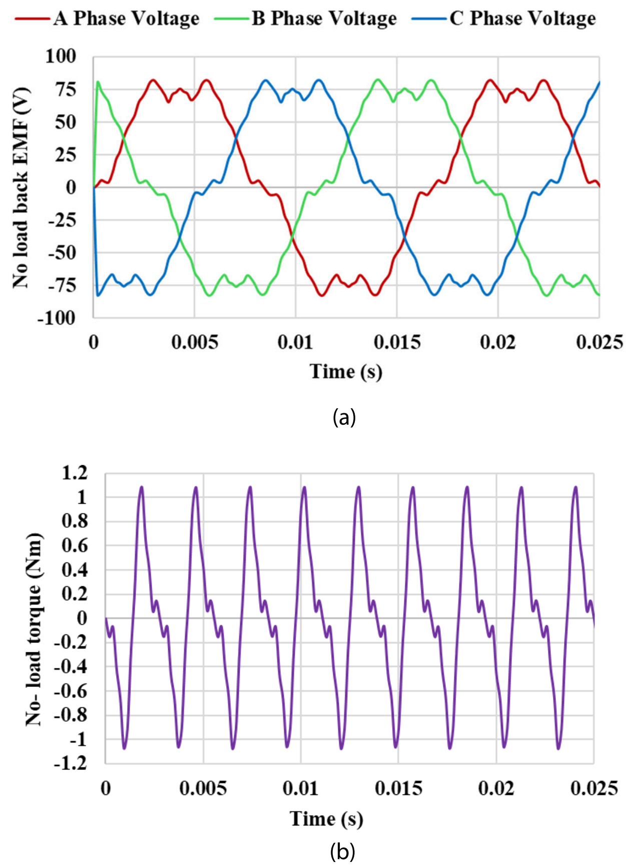


FIGURE 9. (a). Back-EMF @ 900 rpm with 1 A field current.(b). No-load torque or cogging torque @ 900 rpm with 1 A field current.

having frequency, $\omega_e/2$. This HW is positioned on the rotor in such a way that it generates the same number of poles as from the SH-MMF component. It is noteworthy that poles of the FC of this stator MMF and FW produce equal numbers. Thus, linking rotor HW with SHC of stator MMF as well as linking FC present in stator MMF with rotor FW help to achieve the brushless procedure of this suggested technique.

III. ANALYTICAL PERFORMANCE ANALYSIS BY 2-D FINITE ELEMENT METHOD (FEM)

To present the operating principle and effectiveness of the proposed BL-WRSM, a 2-D Finite Element Method (FEM) was utilized.

A. NO-LOAD ANALYSIS OF PROPOSED BL-WRSM

No-load analysis of the suggested machine helps indicate the presence of torque ripples in the proposed machine during the motoring operation. Firstly, DC causes excitation in the FW on the rotor thus simulating the WRSM in a no-load mode. The value of the field current was 1 A. No-load analysis of the proposed machine was performed at 900 rpm, i.e. the actual speed of this newly proposed machine. The no-load voltage and no-load torque can be viewed in Fig. 9(a) and Fig. 9(b), respectively. The voltages with RMS value or back EMF of

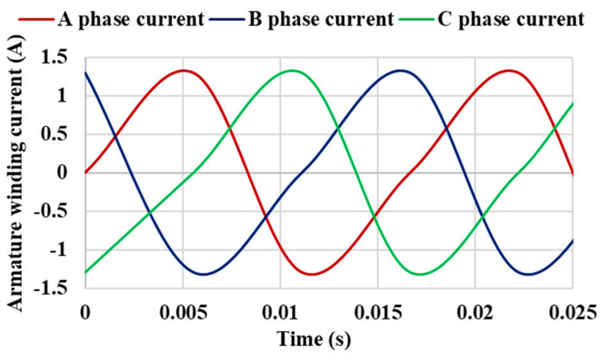


FIGURE 10. Input currents of armature winding.

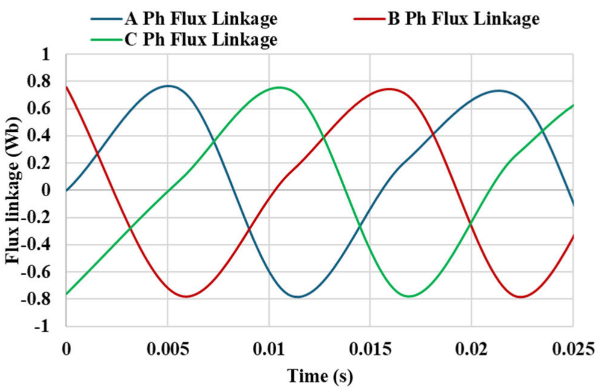


FIGURE 11. Flux linkages with armature winding of proposed BL-WRSM.

56.7837 V were achieved and no-load/cogging torque was −0.0003578 Nm.

B. LOAD ANALYSIS OF PROPOSED BL-WRSM AT RATED SPEED

Load analysis of the proposed brushless machine is performed to evaluate average running torque, torque ripples, flux density, and DC in field winding. Average running torque depends on the machine rating while the torque ripples should be minimum. Similarly, flux density should be less than 2 Tesla to avoid magnetic saturation and overheating in the machine. Analysis, as well as verification of this proposed brushless topology, was performed through 2-dimensional FEA using JMAG Software. A balanced 3-phase sinusoidal current is delivered to the stator or armature winding of BL-WRSM, with an RMS value of 3.1815 A at 60 Hz frequency. Flux density, B, has been contrived at the rated load case. From Fig. 12(a), it is also obvious that the flux density of this proposed BL-WRSM is under 2 Tesla. Fig. 10. shows the input armature winding or SW currents for the proposed BL-WRSM. Fig. 11 shows the flux linkage with 3-phase SW when a balanced 3-phase current is given to armature winding.

The current produced by SHC of stator MMF in HW can be visualized in Fig. 13(a). Current in this HW is alternating and in steady state, its maximum value is 1.286 A. Voltage induced in HW due to inherently SHC is alternating which is then converted to DC using a rectifier. This DC is supplied to FW of the rotor.

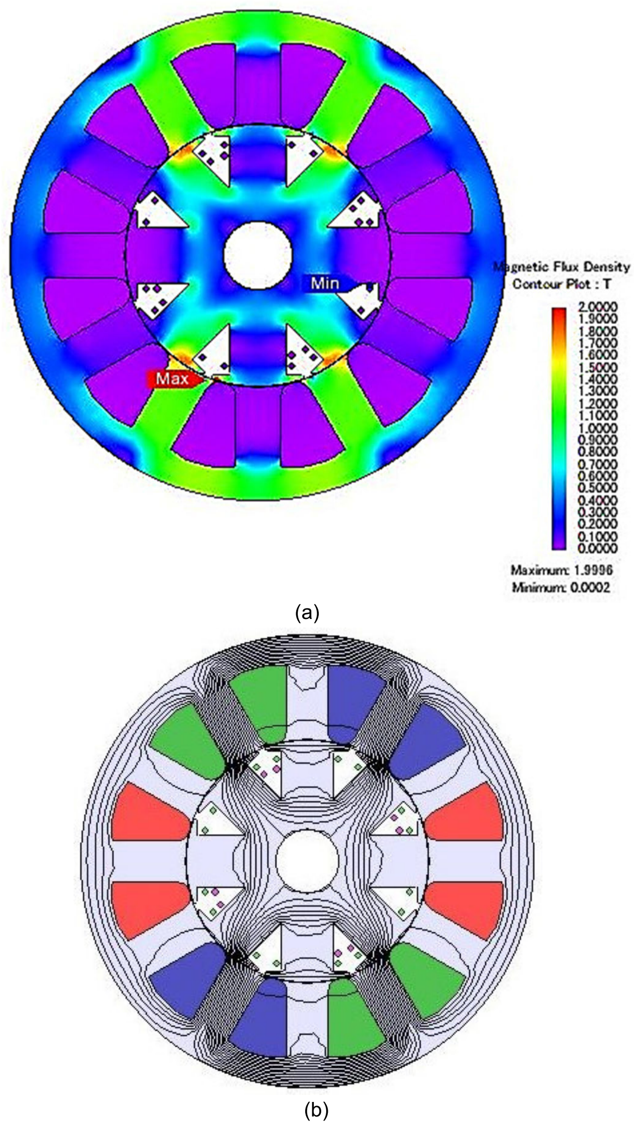


FIGURE 12. (a). Flux density distribution of proposed BL-WRSM at rated speed. (b). Flux line distribution of proposed BL-WRSM at rated speed.

Direct current (DC) in rotor FW has been depicted in Fig. 13(b), which in the steady state has an average or mean value of 1.283 A. After 0.3 s, the field current becomes constant which helps unidirectional torque with minimum torque ripples.

The output torque of 8-pole, 12-slot suggested BL-WRSM can be visualized in Fig. 14(a). The average torque value is 8.39 Nm while torque ripples are 1%. For the calculation of torque ripples the zoom torque diagram is given in Fig. 14(b). of this newly suggested BL-WRSM. From Fig. 14(b) it has been observed that the maximum torque is near 8.43 Nm and the minimum torque is 8. 38 Nm. From this information, torque ripples were calculated which are 1% in the suggested machine. Hence with lower torque ripples the efficiency of the suggested machine is higher.

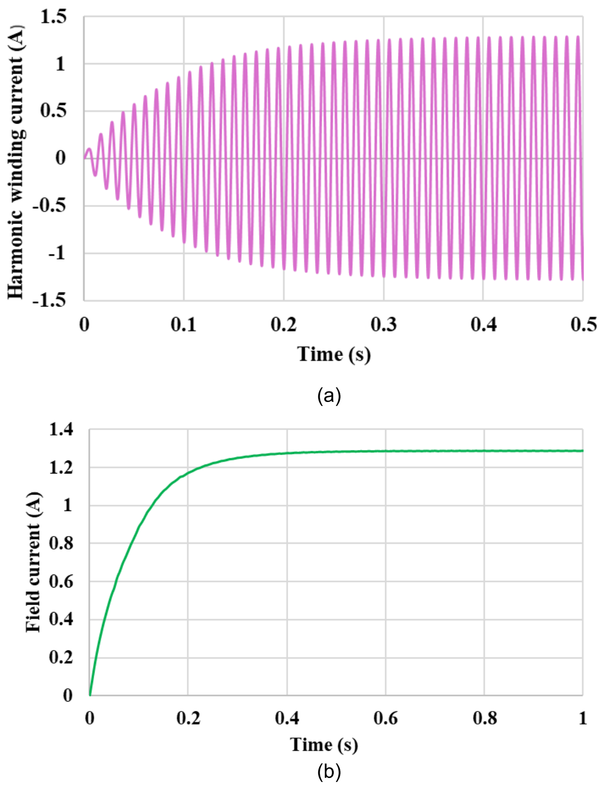


FIGURE 13. **(a). Induced harmonic current in harmonic winding of proposed BL-WRSM. (b). Induced field current in field winding of proposed BL-WRSM.**

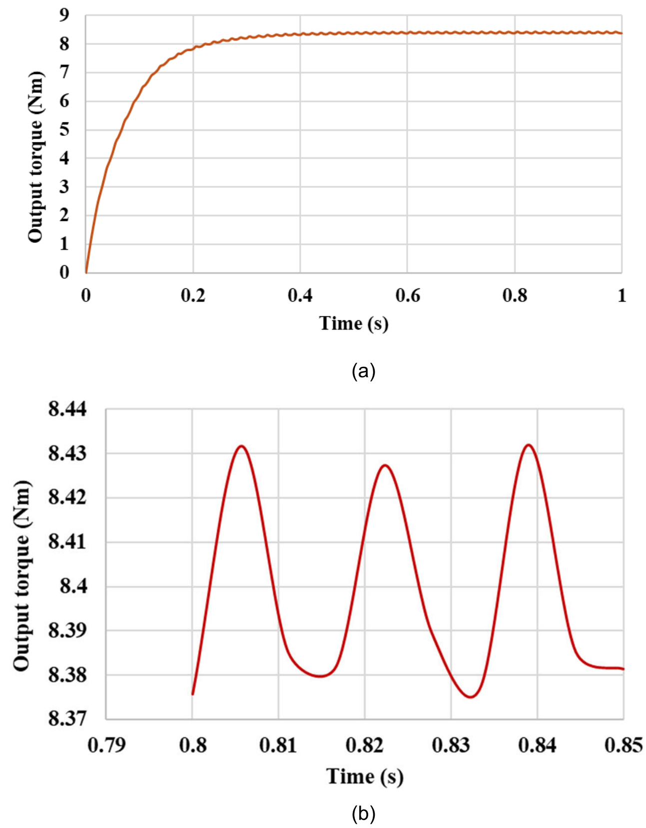


FIGURE 14. **(a). Output torque of proposed BL-WRSM. (b). Steady states output torque to observe torque ripples.**

A comparison between suggested BL-WRSM and conventional WRSM (C-WRSM) was made to verify the usefulness of brushless topology. The C-WRSM with brushes and external DC supply is a benchmark used to validate the performance of any novel BL-WRSM topology. Many existing studies such as [19] have also compared their design with C-WRSM. Any novel BL-WRSM design exhibiting average torque similar to C-WRSM with less torque ripples, is considered to be the better design. Both machines have the same design parameters. Their stator and rotor dimensions, magnitude of currents in the SW, air gap length between stator and rotor, SW turns per phase, poles of FWs, and rotating speed of machines are the same. However, DC was given to rotor FW from an external DC source with the help of brushes in C-WRSW. Slip rings were also used in C-WRSM. There is no need for brushes or slip rings in the proposed BL topology. The proposed BL-WRSM topology employs HW on the rotor to induce AC voltages in it.

The average, maximum and starting torques are higher in C-WRSM as compared to proposed BL-WRSM. Torque ripples in both machines are nearly the same. Due to the presence of HW in the rotor of the proposed brushless WRSM, there are some additional copper losses in the rotor. Similarly, core losses are slightly increased due to the presence of inherent SHC in the stator MMF of the proposed BL-WRSM. From Fig.15(a) output torque of C-WRSM can be viewed.

Fig.15(b) shows the current given to rotor FW directly from an external DC supply using brushes. It was seen that the proposed BL-WRSM has achieved a small lesser torque of C-WRSM but not equal to the torque of C-WRSM. It is due to C-WRSM directly getting DC supply from an external DC source to its FW with the help of brushes. Table 3 shows the performance comparison between C-WRSM and the proposed BL-WRSM.

Existing Brushless WRSM [31] and proposed BL-WRSM were also compared with each other. After analysis, it was seen that the proposed BL-WRSM topology has advantages over existing BL-WRSM. For a fair comparison between both machines, both machines have the same stator and rotor inner and outer dimensions. There is the same air-gap length for both machines. Armature winding turns per phase of both machines were equal. Similarly, the equal number of FW turns, equal number of turns of HW, the same number of poles of FW, and the rotational speeds of both machines are the same.

From the results of Table 3, both machines contain zero starting torque as brushless synchronous motors are not self-starting. Current in HW increases gradually causing field current to increase gradually. After 0.3 s, the field current reaches a steady state and torque attains a constant value at 8.39 Nm. However, the average torque of the proposed BL-WRSM is 8.39 Nm while the average torque of the

TABLE 3. Performance comparison between C-WRSM and proposed BL-WRSM.

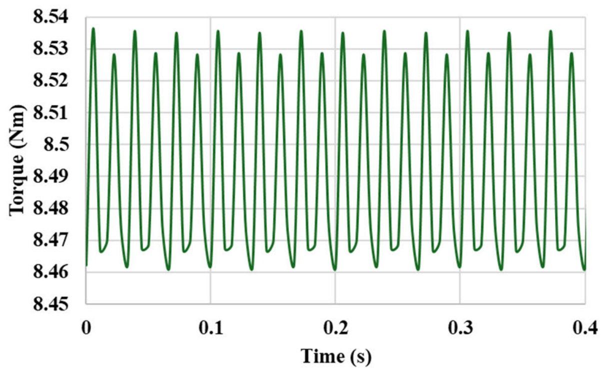
Parameter	Units	C-WRSM	Proposed BL-WRSM
Stator current	A_{rms}	3.1815	3.1815
Starting Torque	Nm	8.4623	0
Maximum Torque	Nm	8.5365	8.43
Average Torque	Nm	8.49	8.39
Torque Ripples	%	1	1
Field current	A	1.28	1.29
Harmonic Winding current	A_{rms}	0	1.286
Core loss	W	53.15	54.10
Stator copper loss	W	8.1	8.1
Harmonic winding copper loss	W	0	0.53
Field winding copper loss	W	3.67	3.73
Efficiency	%	92.5	92.2

TABLE 4. Performance comparison between proposed BL-WRSM and existing BL-WRSM At rated speed.

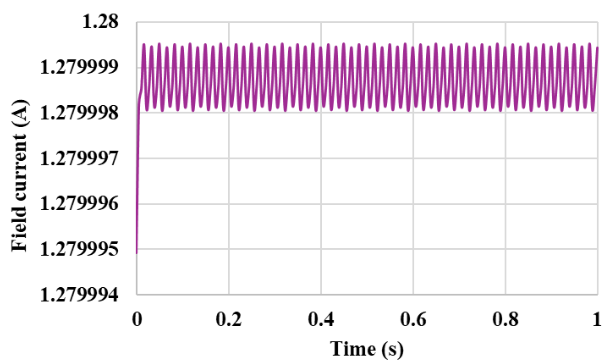
Parameters	Units	Existing BL-WRSM [31]	Proposed BL-WRSM
Power	W	777	791
Torque	Nm	8.24	8.39
Torque ripples	%	18.41	1
Stator winding current	A_{rms}	4.5	3.1815

existing BL-WRSM is 8.24 Nm which indicates proposed machines have a higher average torque. There are 1% torque ripples in the proposed BL-WRSM while 18.41% torque ripples are present in existing BL-WRSM [31]. Due to lower torque ripples in the proposed BL-WRSM, the efficiency of the suggested machine is better than the existing BL-WRSM.

Also, the SW input current is 3.1815 A_{rms} in the proposed machine at a frequency of 60 Hz, while the input current to existing BL-WRSM is 4.5 A_{rms} having 60Hz frequency. With low value of input current as compared to existing BL-WRSM input current also indicates that the proposed BL-WRSM has an advantage over existing brushless machine. Hence with less armature current, there are less copper losses in the proposed machine over an existing machine. Hence proposed BL-WRSM exhibits higher efficiency as compared to the existing brushless machine presented in [31]. A comparison between both machines is shown in Table 4. The results indicate that the proposed machine exhibits more output power with less torque ripples as compared to existing BL-WRSM [31].



(a)



(b)

FIGURE 15. (a). Output torque of C-WRSM. (b). Field current of C-WRSM.

IV. CONCLUSION

A novel BL-WRSM has been presented, in which the brushless working of the suggested machine is performed by utilizing an inherited SHC of stator MMF. It is worthy to mention that the inherent SHC of this proposed machine helps to reduce torque ripples. Moreover, the proposed machine exhibits high torque at rated speed. The existing brushless excitation schemes use additional hardware or special winding arrangements to generate harmonics which increase the cost of machines but in this research, inherently present harmonic is used to generate voltages in harmonic windings.

In the proposed BL-WRSM, there is a need for a single inverter, which helps low-cost system. In the proposed topology, simple 3-phase winding is present on the stator. Neither double inverters nor a special SW arrangement is required. However, due to the presence of HW on the rotor, power loss exists in rotor HW as well. Applications for the proposed BL-WRSM are regions where sparking due to brushes must be prevented, i.e., aircrafts, oil and gas industries, etc.

The suggested topology has obtained the required torque at the rated speed, but the performance of the suggested machine in terms of average torque is lagging a little bit behind the C-WRSM. Nevertheless, the benefit of the proposed machine is working without brushes, which would result in less maintenance as required in C-WRSM.

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