Bi-Furcated Stator Winding Configuration in Three-Phase Induction Generators for Wind Power Generation

P. MEENA[1], (Member, IEEE), V. PREMA[1], (Senior Member, IEEE),
M. S. BHASKAR[2], (Senior Member, IEEE),
AND DHAFER ALMAKHLES[2], (Senior Member, IEEE)

[1]Department of Electrical and Electronics Engineering, B.M.S. College of Engineering, Bengaluru 560059, India
[2]Renewable Energy Laboratory, Department of Communications and Networks Engineering, College of Engineering, Prince Sultan University, Riyadh 11586, Saudi Arabia

Corresponding authors: V. Prema (premav.eee@bmsce.ac.in) and M. S. Bhaskar (sagar25.mahajan@gmail.com)

ABSTRACT The concerns over the increase in carbon footprints and global climatic changes have given momentum to find ways that reduce the use of fossil fuels to generate electricity. Offshore and onshore windmills for electricity generation are viable options for bulk power generation. A wind generation system has a variable frequency variable voltage supply at the induction generator terminals in response to the changes in the wind velocity and in turn, the speed of the wind turbine. There is a need for an additional power electronic interface to maintain the frequency and voltage at the terminals of the wind generator constant. This paper introduces a novel three-phase Bifurcated Winding Induction Generator (BWIG) comprising a bifurcated set of stator windings. A prototype model has been developed by bifurcating the stator windings of a three-phase induction machine. One part of the winding acts as the excitation winding, and the other half is used as output winding capable of producing three-phase voltages at a constant frequency at all speeds of the prime over. The machine is tested for sub and super synchronous speeds and the characteristics plotted. The flux analysis of the machine is simulated using Ansys Maxwell software. The voltage is controlled by a simple off-on control implemented using a digital controller, TMS320F28335.

INDEX TERMS Bifurcated stator winding configuration, closed loop, flux analysis, three phase induction generators, wind energy.

I. INTRODUCTION

The rising cost of nuclear and fossil fuels is an encouragement to the deployment of non-conventional energy sources. On-shore and off-shore windmills for electricity generation have also emerged as a viable option for bulk power generation. If the wind generator needs to be connected to the grid under conditions of variable wind velocity, there is a need for an additional power electronic interface to maintain the frequency and voltage at the terminals of the wind generator constant. In the case of grid-tied systems, it is essential to have control over the active power delivered to the grid under conditions of variable speed and load. Some approaches towards this include a variable speed, constant voltage, and frequency

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converter with de-coupled active and reactive power control [1]. This concept is used in double fed induction generator configuration where the rotor is of wound rotor type and the slip rings are connected to a three-phase PWM inverter, the output of which through transformers is fed back to the grid thereby power delivered to the grid is always at constant frequency and a constant voltage of the grid even though the prime mover speed and hence slip varies [2]. Fan *et.al.* [3], proposed a novel brushless doubly-fed machine for the generation of wind power. Constant output voltage and optimization of efficiency for a wide range of wind speeds were the keys. Permanent Magnet machines are in high demand these days due to their high torque density and efficiency. Many magnetic concepts such as Vernier Machine and magnetically geared Permanent Magnets are proposed [4]–[6].

Another approach is to provide a self-excited induction generator with capacitors connected to the terminals of the generator that are connected to the grid through an AC-DC-AC link at the stator which helps maintain the frequency and voltage constant [7]. The main advantage of such a machine is that they do not require any additional power supply for the generation of a magnetic field [8]. Research is in progress with both single-phase and multiphase machines [9]. In [10], a five-phase Induction Generator is proposed for wind energy generation. The model was tested for varying wind speeds and loading conditions. It was observed that the power generated is higher than that of a three-phase generator. Yet another approach is that of TSCAOI (Two series-connected and one isolated) configuration of a cage rotor variable speed induction generator capable of producing single-phase AC voltage at a constant frequency. In this case, there are two sets of winding namely, the excitation and the power winding. Either of the two (isolated or two series-connected) may be used as power or excitation winding [11].

In [12], a novel squirrel cage induction generator is introduced. A 3-phase cage motor is converted to generate a constant frequency supply for different rotor speeds without intervention of a power electronic converter. It works satisfactorily for both above and below synchronous speeds. Experimental results are obtained from a 2kW prototype generator. In [13], a novel configuration is proposed to connect a Doubly fed Induction Generator (DFIG) to a DC microgrid. A three phase DFIG is connected in open winding configuration and 3-leg rectifiers are connected to each side of the stator winding. The experimental results of the proposed dual converter topology show that there are no speed or torque oscillations. Zero sequence current is also reduced.

Many schemes based on dual-stator induction generators for wind energy conversion are proposed [14]–[17]. In [14], a dual stator brushless doubly-fed induction generator is proposed for wind energy conversion. A direct voltage control strategy for stand-alone operation is proposed. The controller is implemented with the dSpace control board. The results are promising. In [15], a novel control strategy for a dual stator induction generator is proposed. JC Wu, et.al. propose a novel power conversion interface for a self-excited induction generator [16]. This has a diode bridge rectifier and an inverter to obtain a fixed frequency ac. A power capacitor and a power converter serve as the excitation system. The need to provide constant frequency and voltage outputs for variable speed induction generators [18] are critical.

Reluctance based generators have also attracted attention in wind power generation due to the advantages of reduced cogging torque, ability to operate at lower wind speeds, etc. In [19], the authors have analysed the excitation conditions for increased generation efficiency. This is achieved by reducing the copper losses. Reference [20] proposes a novel hybrid reluctance generator. Here permanent magnets are accommodated in stator slot opening. This enhances torque density. This configuration has added advantages of robust rotor structure, avoidance of risk of demagnetisation and simple
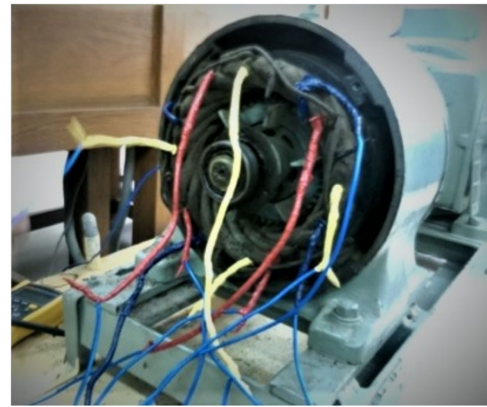

FIGURE 1. Implementation of BWIG.

TABLE 1. Specifications of the induction machine.

DC Generator		Three Phase Squirrel Cage Induction Motor	
Make	Thomson Houston Co.	Make	Crompton Greaves
SL. No	940571-1	SL.No	6212661
kW	2.8	kW	3.7
Volts	110	Volts	400
Amps	25.4	Amps	7.8
RPM	1450	RPM	1450
		Motor Starter	5HP 400V

design. A new switching strategy for winding is proposed for hybrid excited reluctance machine in [21]. This improves the regulation of flux in the machine and gives a constant output voltage for a wide range of wind speeds.

This paper introduces a novel three phase induction generator where the stator windings of a traditional machine are bifurcated. Among the two sets of bifurcated stator windings, one set serves as excitation winding and the other one as power/output winding. This produces a constant frequency-three phase sinusoidal voltage at varying speeds, without any frequency controller. For experimental analysis, a prototype machine is constructed from an existing three phase induction machine. The machine characteristics are plotted at sub and super synchronous speeds of operation for variations in load. The flux analysis of the machine is simulated using Ansys Maxwell software. The output voltage is controlled by a simple off-on control implemented using a digital controller, TMS320F28335. The main benefit of this configuration is that it maintains a constant frequency output voltage for varying ranges of wind speed. This machine is most suited for a power generation from wind energy.

II. BIFURCATED WINDING INDUCTION GENERATOR (BWIG)
A. CONSTRUCTION OF BWIG
An existing cage rotor induction machine with the specifications given in Table 1 is chosen for the experiment [22]. In the new configuration, stator windings of the cage rotor
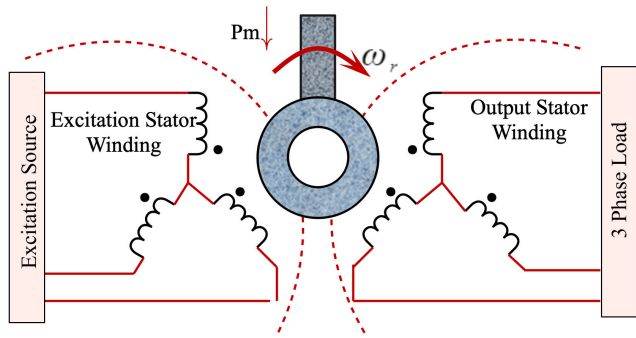
FIGURE 2. Schematic diagram of BWIG.

FIGURE 3. Constant frequency operation at different speeds.

FIGURE 4. Excitation current versus rotor speed.

induction machine are bifurcated so that 50% of the windings of each phase were star connected as the excitation winding. The other half of the windings are used as three-phase output winding facilitating a connection to an external load or the grid. There are 36 slots for the stator windings which implied 12 slots per phase and 3 slots per pole per phase. An approximate halfway point in each winding is identified. Since there are 12 slots per phase the winding was divided in half by cutting the winding after 6 slots. The resistance and inductance of each half of the winding are measured using a multimeter and an LCR meter and the values obtained for each half of the winding of every phase are verified.

B. CHARACTERISTICS OF BWIG

The novel BWIG is configured to be driven as a generator by using a DC motor as a prime mover to simulate a wind turbine. The DC motor is run using a rectifier at synchronous, sub-synchronous, and super-synchronous speeds, and behavioral characteristics of excitation and power windings are obtained. The picture of bifurcated stator winding terminals is shown in Fig. 1. Fig. 2 shows how each half of the stator windings is connected to the excitation source and the three-phase load.

When the connections are made as shown in Fig. 2, it is seen that in response to the variations in excitation voltage, the output voltage varied without any change in frequency. The maximum value of output voltage is kept at 150 volts to avoid any damage to the windings since they are rated for 200 volts. It is observed that the bifurcated configuration completely eliminates the need for a power electronic interface between the generator and the grid in order to keep the frequency constant at 50 Hz. The complexity of active power control problems during variable speed and load operation in the case of a conventional asynchronous generator is also eliminated. The constant frequency of operation is observed in the waveforms captured at different speeds of operation of the prime mover and the same is shown in Fig. 3.

Another advantage of the bifurcated configuration is that, at higher wind speeds, the excitation and hence the active excitation power required to maintain a constant output voltage is lower than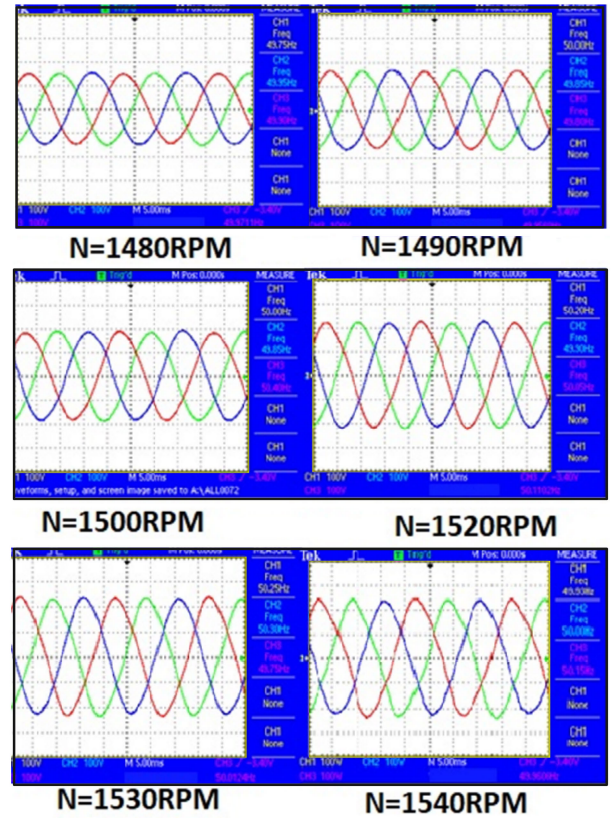 that at lower speeds of operation. From the graph in Fig. 4 it can be seen that as the rotor speed is increased, the excitation current drawn by the motor is decreased which shows that a lower value of excitation current is enough to maintain the output voltage at the required level.
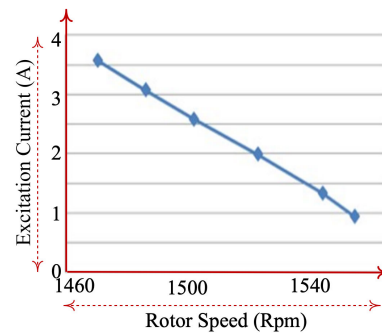
Experiments were conducted with different load conditions to analyse the excitation and output power. The experimental set up is shown in Fig. 8. A DC motor is used as the prime mover. Three phase excitation is given through a 3-phase auto-transformer. The tabulations for different speeds at various loads are shown in tables 2 to 6. I_{e1}, I_{e2} and I_{e3} are
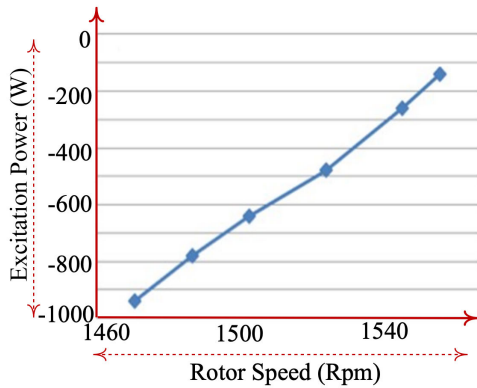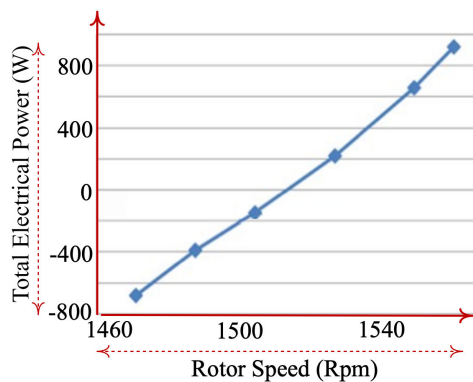
FIGURE 5. Excitation power versus rotor speed.

FIGURE 6. Total electrical power versus rotor speed.

GENERAL DATA	VALUE
Rated Power Output	3.5kW
Rated Voltage	415V
Rated Speed	1450rpm
Frequency	50Hz
Number of Poles	4
Winding Connection	Delta
Stator Slots	36
Rotor Slots	28
Stator Outer Diameter	170mm
Stator Inner Diameter	103mm
Rotor Outer Diameter	102.9mm
Rotor Inner Diameter	66.54mm
Shaft Diameter	38mm
Rotor Slot Height	17.98mm
Operating Temperature	50°C

the three phase excitation currents. the voltage and current of the prime mover are also given in the table. Tabulations are carried out for five different values of output powers, 184W, 280W, 560W, 800W and 1kW, as shown in tables 2 to 6. each table gives the voltage, current and power for different values of speed. A negative value of excitation power indicates that power is being drawn by the excitation winding of the generator whereas a positive value of power indicates that power is being supplied by the generator to the excitation source. From the above readings it can be observed that at sub-synchronous speeds, the excitation winding is drawing power from the source whereas for super-synchronous speed, the excitation winding is supplying power back to the grid. It is also observed that at higher loads, the point of power reversal shifts to higher speeds.

It can be observed from Fig. 5, that at sub-synchronous speeds the excitation power was high and the machine drew large power from the mains. This power goes on decreasing as the speed increases beyond synchronous speed. From the graph it can be predicted that beyond a speed of 1560 RPM the excitation power drawn would almost reach zero and power reversal (power supplied by the generator to the source) would occur signifying that the excitation winding is also feeding power to the grid. This result helps

in fixing the operating speed range for the new generator configuration.

From the graph shown in Fig. 6 it was observed that the total active power output varies with changes in motor speed as is typical in any wind turbine application.

III. FLUX ANALYSIS

It is very important to analyze the flux distribution of any novel machine design to understand the performance [23]. Finite Element Method (FEM) is one of the most popular techniques to analyze the performance of any machine [24]–[28]. In [25], Permanent Magnet Synchronous Machine is analyzed using FEM. It helps to simulate the output voltage of the machine for different magnetic shapes and dimensions. The flux linkage coefficient for radial and axial field and cogging torque are also analysed. Two different types of Induction Generators are analysed and compared in [26]. In [27], self-excited grid connected Induction Generators are analyzed. FEM could accurately predict the output power and line currents of the generator. FEM can also be used to calculate the model parameters of a machine [28].

In this paper, the simulation software Ansys Maxwell, which is based on finite element analysis is used for this purpose. Using this software, the flux distribution of the proposed machine is compared with that of a conventional induction generator. Fig. 7 shows the flowchart of the overall process simulated using ANSYS software. The Table 2 gives the detailed technical and physical dimensions of the squirrel cage rotor machine under study.

In order to analyse the performance of the BWIG given specifications of the machine are entered in RMxprt along with materials are assigned such as D23-50 for stator and
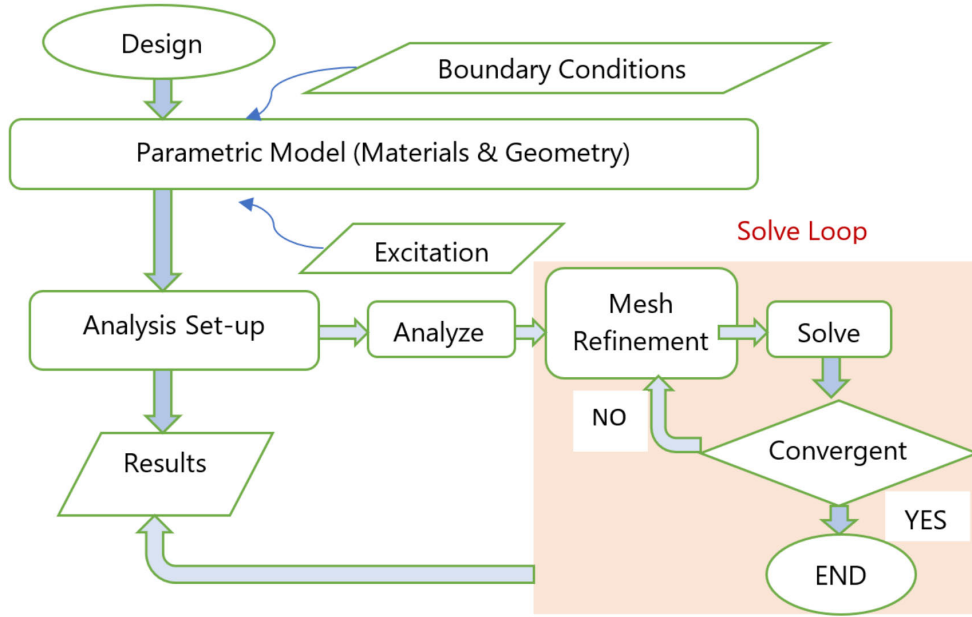
FIGURE 7. Flux analysis flow chart.

TABLE 2. Experimental results for a load of 184W.

Speed (RPM)	Excitation Current(A)			Output Voltage (V)			Output Current (A)			Excitation Voltage (V)			DC Current(A)	DC Voltage(V)	Excitation Power(W)	Output Power(W)
N	Ie1	Ie1	Ie3	Vo1	Vo2	V03	Io1	Io2	I03	Ve1	Ve2	Ve3	Idc	Vdc	We	W0
1500	2.41	2.35	2.17	147	146	146	0.33	0.33	0.33	106	111	108	3.7	110	-460	160
1520	2.22	2.07	2	151	150	150	0.35	0.37	0.38	102	106	106	10.5	110	140	184
1540	3.42	3.18	3.15	151	150	151	0.35	0.37	0.35	98.7	102.1	102.3	19.39	110	860	184
1480	3.55	3.54	3.38	154	152	153	0.34	0.34	0.34	124.8	127	125.3	0.03	110	-1200	184
1475	4.32	4.33	4.1	152	151	152	0.34	0.33	0.35	128.7	133	130	-0.03	110	-1600	184

TABLE 3. Experimental results for a load of 280W.

Speed (RPM)	Excitation Current(A)			Output Voltage (V)			Output Current (A)			Excitation Voltage (V)			DC Current(A)	DC Voltage(V)	Excitation Power(W)	Output Power(W)
N	Ie1	Ie1	Ie3	Vo1	Vo2	V03	Io1	Io2	I03	Ve1	Ve2	Ve3	Idc	Vdc	We	W0
1500	2.76	2.61	2.53	150	147	148	0.58	0.6	0.58	114	118	114	2.54	110	-720	280
1520	2.22	1.96	1.92	152	151	152	0.61	0.61	0.58	106.2	109	108.5	11.35	110	140	280
1540	3.71	3.33	3.24	152	151	152	0.61	0.61	0.58	100.2	104.6	109.2	27.3	110	960	280
1480	3.41	3.29	3.06	149	148	149	0.6	0.6	0.58	121	126	120.2	0.48	110	-1100	280
1470	4.46	4.62	4.25	148	147	149	0.65	0.63	0.58	128	136	129	0	110	-1720	280

rotor and exported to ANSYS MAXWELL. the specifications for the stator and rotor are given in tables 8 and 9 respectively.

The physical dimensions and material details of the machine are loaded in the software for parametric model. Excitation and boundary conditions are applied. MESH operations are chosen to perform FEM analysis. Maxwells equations are iteratively evaluated at each mesh node. The tool,

RmXprt is used to simulate the performance of the machine under rated conditions.

It can be observed from the figures that as the new machine windings are bifurcated, it does not produce a rotating magnetic field that hitherto existed in a conventional induction generator. Thus, the output flux linkages are sinusoidal as shown in Fig. 9. The output voltage variation for different

TABLE 4. Experimental results for a load of 560W.

Speed (RPM)	Excitation Current(A)			Output Voltage (V)			Output Current (A)			Excitation Voltage (V)			DC Current(A)	DC Voltage(V)	Excitation Power(W)	Output Power(W)
N	Ie1	Ie1	Ie3	Vo1	Vo2	V03	Io1	Io2	I03	Ve1	Ve2	Ve3	Idc	Vdc	We	W0
1500	3.01	2.97	2.85	149	148	149	1.22	1.21	1.2	123	127	124	2.95	110	-1000	544
1520	1.74	1.61	1.69	151	149	150	1.24	1.22	1.22	113	114	111	14	110	120	560
1540	2.43	2.39	2.39	151	148	149	1.2	1.17	1.2	107	107	106.4	21.07	110	620	532
1480	4.1	3.84	3.95	149	148	148	1.22	1.22	1.2	134	134	130	0.08	110	-1540	532

TABLE 5. Experimental results for a load of 800W.

Speed (RPM)	Excitation Current(A)			Output Voltage (V)			Output Current (A)			Excitation Voltage (V)			DC Current(A)	DC Voltage(V)	Excitation Power(W)	Output Power(W)
N	Ie1	Ie1	Ie3	Vo1	Vo2	V03	Io1	Io2	I03	Ve1	Ve2	Ve3	Idc	Vdc	We	W0
1500	3.34	3.22	3.28	149	149	149	1.83	1.78	1.8	133	135	132	3.66	110	-1288	800
1520	1.78	1.5	1.38	151	149	150	1.83	1.78	1.8	122	123	122	12.83	110	-320	808
1540	2.18	2.08	2.06	150	148	150	1.82	1.78	1.81	113	114	115	25	110	600	800
1480	4.88	4.83	4.64	150	149	150	1.83	1.8	1.82	145	147	143	0.02	110	-1868	816

TABLE 6. Experimental results for a load of 1kW.

Speed (RPM)	Excitation Current(A)			Output Voltage (V)			Output Current (A)			Excitation Voltage (V)			DC Current(A)	DC Voltage(V)	Excitation Power(W)	Output Power(W)
N	Ie1	Ie1	Ie3	Vo1	Vo2	V03	Io1	Io2	I03	Ve1	Ve2	Ve3	Idc	Vdc	We	W0
1500	3.91	3.78	3.68	150	149	149	2.41	2.41	2.24	143	145	141	3.91	110	-1640	1076
1520	1.51	1.36	1.41	151	150	151	2.43	2.42	2.46	129	131	128	15.06	110	-380	1084
1543	1.39	1.28	1.29	150	150	150	2.43	2.4	2.44	121	123	122	25	110	320	1080
1480	5.67	5.41	5.6	148	147	147	2.38	2.38	2.42	153	155	151	-0.09	110	-1640	1048

FIGURE 8. Experimental set up of BWIG.

FIGURE 9. Output flux linkages in the BWIG at 1530 rpm using ANSYS.
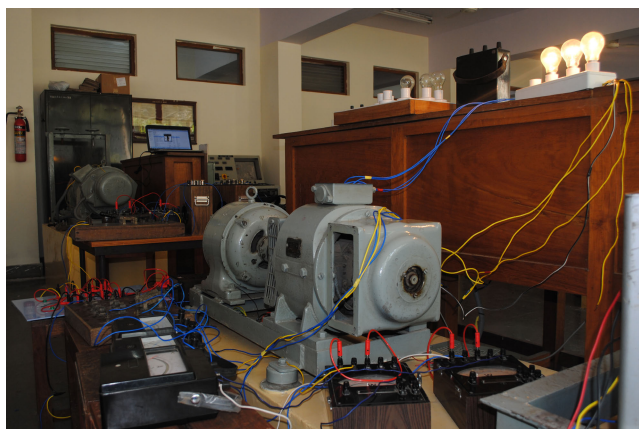
speeds and excitation values were tested using ANSYS software. Fig. 10 shows the output voltage for the rated speed of 1450rpm. It is observed that the output frequency was constant at 50Hz for any speed of operation of the prime mover.

IV. PERFORMANCE COMPARISON OF BWIG WITH EXISTING CONFIGURATIONS

A detailed comparison of the proposed machine with the existing induction generators is carried out in this section.
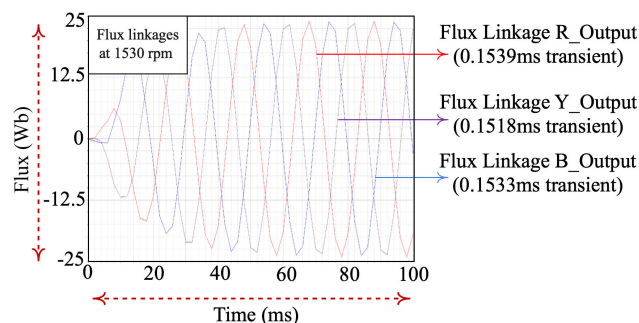
Reference [29] discloses a generator with a particular stator winding pattern specifically designed to generate less torque ripple during working. The proposed electrical generator comprises a stator with a pair of multi-phase windings, one of the windings being a wye type winding and the other one of the windings being a delta type winding. Whereas we propose a three-phase induction generator driven by a variable speed prime mover. Here, a bifurcated stator winding is being used for generating a three-phase sinusoidal voltage at constant frequency at all speeds of the prime over. Reference [30] discloses a generator comprising a stator with two sets of
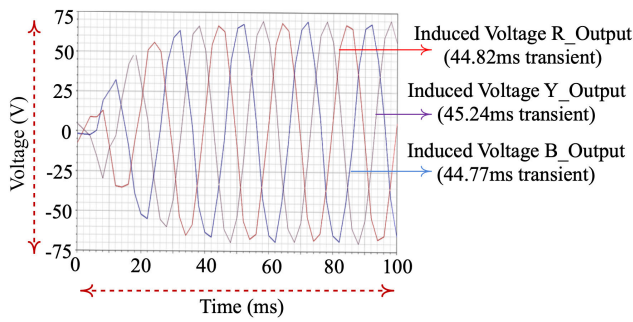
FIGURE 10. Simulated output voltage for N=1450rpm.

TABLE 8. Specifications of stator.

Parameters	Values
Outer Diameter	170mm
Inner Diameter	103mm
Length	140mm
Stacking Factor	0.95
Steel Type	D2350
Number of Slots	36
Slot Type	4
Rotor Slots	28

TABLE 9. Specifications of rotor.

Parameters	Values
Stacking Factor	0.95
Number of Slots	28
Slot Type	1
Outer Diameter	102.2mm
Inner Diameter	38mm
Length	140mm
Steel Type	D2350

winding and the rotor induces voltage in the first set of winding. A converter is coupled to the first set of stator windings to convert generated ac to dc. The second set of stator windings is coupled to another converter, which generates control voltages and/or control currents. The BWIG proposed in this paper does not use any type of converter in pulse width modulation (PWM) mode. The proposed generator works without a power electronic interface or capacitor, but driven by a variable speed prime mover. Reference [31] relates to an electrical machine having two part windings, a core having slots in which the first and second sub-coil are wrapped and a switching circuit for coupling the first sub-winding to the second partial winding. the part windings can be either connected in series or parallel for a higher or lower voltage. But, the BWIG presented in this paper does not provide the placement of windings in grooves for establishment of

symmetrical field distribution. This machine points about use of excitation winding set to maintain the frequency.

The induction generator proposed in [32] has one or more energy windings and one or more auxiliary windings where the auxiliary windings have fixed and switched capacitors which are used to control the induction generator output under variable load conditions. The auxiliary windings are electrically and magnetically isolated from the energy windings. But the BWIG presented in this paper completely eliminates the need for a power electronic interface between the generator and the grid. Further, the active power control problems during variable speed operation in case of conventional asynchronous generator are also eliminated. The machine in [33] comprises three-phase stator windings serving as primary windings, and connected to a source of power, three-phase rotor windings serving as a secondary winding, and coupled to magnetic field. Resistive and/or reactive circuits are connected in series with secondary windings to provide the magnetizing currents in the secondary and to increase the efficiency of generator. But the BWIG proposed in this paper eliminates the need for a power electronic interface between the generator and the grid. Moreover, this configuration avoids use of capacitor, which in turn could lead to inrush currents during the voltage build up in induction generators and further add to the requirement of dampers.

A laboratory prototype of a TSCAOI (Two series-connected and one isolated) configuration machine [3] is developed in the lab to have a comparative study with BWIG of the same rating. The performance of BWIG is compared with the TSCAOI configuration. The variation of efficiency at various speeds for both machines is plotted in Fig. 11. It can be observed that the efficiency of the bifurcated stator winding configuration is higher compared to the TSCAOI configuration. The bifurcated stator winding provides a three-phase output when compared to the TSCAOI configuration which gives a single-phase output. Hence, using the bifurcated stator winding configuration, three-phase loads can be operated. It would be appreciated by those skilled in the art that as long as the frequency of the excitation source is fixed, the frequency of the three-phase supply generated by the induction generator remains constant even if the speed of the prime mover varies. This configuration yields a pure sinusoidal three-phase output across the output winding and is suitable for both standalone and grid-connected operations.

The voltage waveforms obtained from the bifurcated configuration are sinusoidal when compared to that obtained from the TSCAOI configuration which has harmonics are shown in Fig. 12. The output voltage of the TSCAOI configuration is not sinusoidal and dominant harmonic contents were present at 100Hz and 150Hz as seen in the corresponding FFT.

The graph shown in Fig. 13 indicates the regulatory nature of the excitation voltage in a stand-alone bifurcated configuration as compared to that of a TSCAOI configuration. As seen in the graph, there are very slight variations in the excitation voltages required to maintain the output voltage
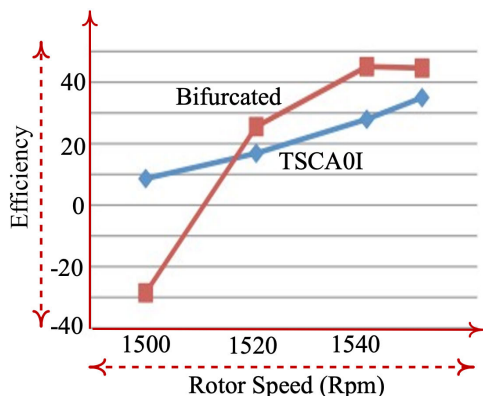
FIGURE 11. Efficiency comparison of bifurcated and TSCAOI configurations at various speed.
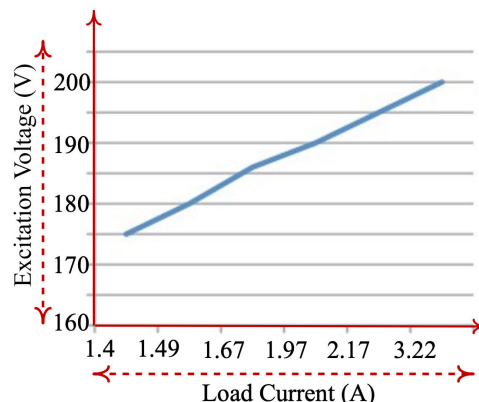

FIGURE 12. Harmonic analysis of TSCAOI configuration.

FIGURE 13. Comparison of excitation voltage variation to maintain the output voltage constant.

FIGURE 14. Variation of excitation voltage to keep the active power constant.

FIGURE 15. Variation in excitation power to maintain a constant power output.

FIGURE 16. Excitation given by inverter.

constant. Therefore, a fast-acting precise controller is useful for closed-loop control of the output voltage of a bifurcated winding generator.

A. GRID -TIED CONFIGURATION OF BWIG

The BWIG is synchronized to the grid. The variation in excitation voltage is observed for various loading conditions after connecting to the grid. It is found that it is possible to control
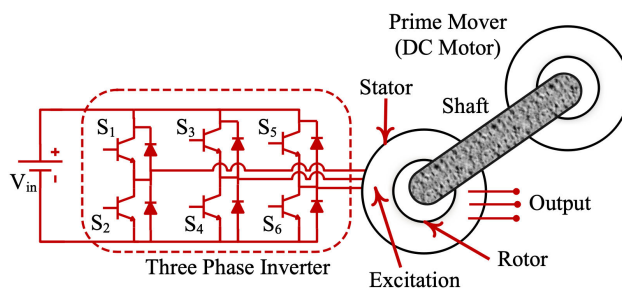
the operation of the system at constant active power whenever there is a variation in load by varying the voltage applied to the excitation winding as shown in Fig. 14. It shows that variations in excitation voltage in response to load variations do contribute to keeping the active power constant. Hence from the graph, the controllability feature of the excitation voltage is evident for active power control in a grid-tied configuration.

The variation in excitation power is also plotted against load current variation as shown in Fig. 15. It can be observed that it is possible to control the active excitation power for
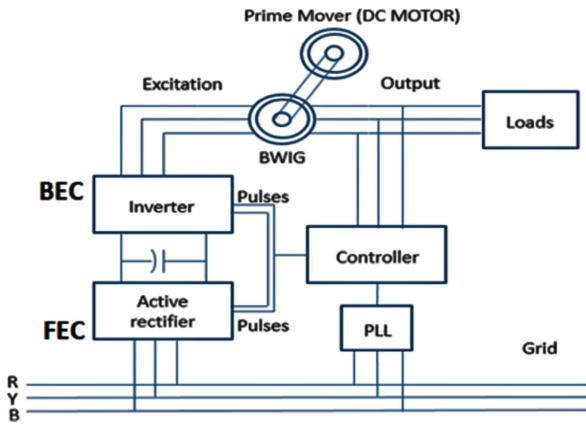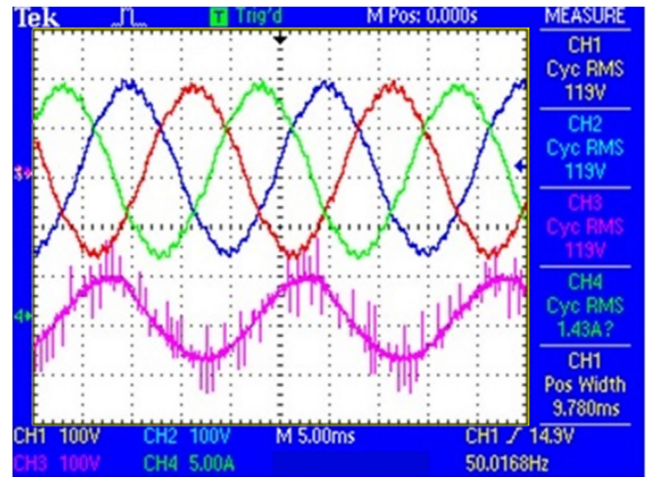
FIGURE 17. Complete system overview.

FIGURE 20. Excitation current and output voltage for m = 0.7.
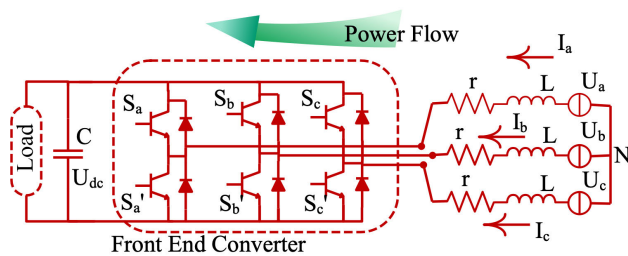
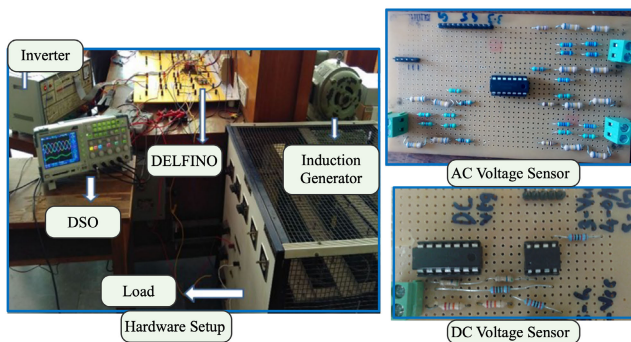

FIGURE 18. Front end converter.

FIGURE 19. Hardware setup.

maintaining a constant output power operation during load variations. The negative values indicate that the excitation source is supplying power and positive values indicate that the induction generator is supplying power to the excitation source. Another advantage of the novel configuration is that in the eventuality of a grid failure machine continues to operate as a standalone unit and the load voltage can be controlled by controlling the applied excitation voltage. Further, there is no capacitor used in the system and the in-rush current problems that exist in self-excited generators are completely eliminated in this configuration.

V. SYSTEM OVERVIEW
It can be seen from section II that, in the proposed generator configuration, the output voltage in stand-alone mode is not constant but it varies with both speed and excitation voltages. The output voltage can be maintained constant by using the power electronic inverter connected as an excitation source as shown in Fig. 16.

To eliminate the use of battery for the inverter, a bridge rectifier can be used for converting AC to DC. The disadvantage of this arrangement is that the rectifier will not allow the reverse power flow. To get maximum out of the generator it is better to allow reverse power flow. Hence Back to Back inverter configuration with back-end inverter (BEC) and front-end active rectifier (FEC) is chosen. The entire system requirement thus becomes as shown in Fig. 17.

In many motor drive applications, when the motor enters into generating mode during breaking, the active power flows from the motor to the source side through BEC and the voltage across the capacitor increases. Similarly, the characteristics of the Bifurcated Induction Generator show that the generator starts pumping back the active power to the source even from the excitation winding after a particular speed, which will be decided by the load. When the active power is pumped back from excitation winding towards the source, the voltage across the DC link capacitor increases beyond the limit. This excess energy stored in the DC link capacitor should be directed towards the source by FEC. The FEC should be operated in such a way that it should draw current at unity power factor, not distorting the source voltage and maintain a voltage across DC link capacitor constant. Fig. 18 shows the circuit diagram of the FEC. Both active and reactive power can be controlled by controlling the phase and magnitude of the converter voltage at points a, b and c.

VI. HARDWARE IMPLEMENTATION OF CONTROLLER
The complete hardware setup is shown in Fig. 19. Delfino TMS28335 is used for generation of PWM signals by implementing sinusoidal Pulse Width Modulation (SPWM). Fig. 20 shows the generator terminal voltage for a modulation index (m) of 0.7. Fig. 21 shows the variation of inverter voltage over modulation index, which defined the control range.
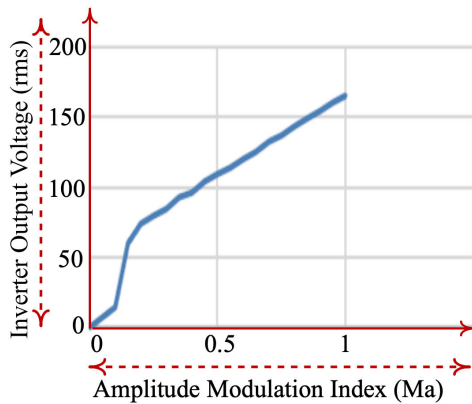
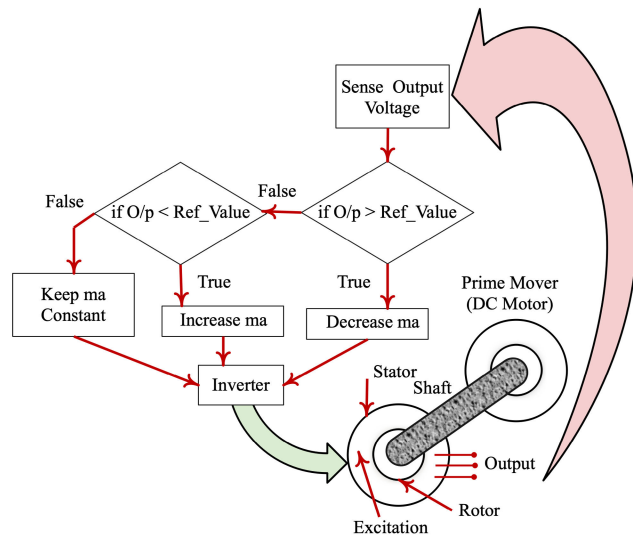**FIGURE 21.** Variation inverter voltage over modulation index.

FIGURE 22. Control algorithm.

Thus the output voltage of BWIG changes with modulation index. The output voltage can be kept constant at desired value by controlling the modulation index. The algorithm is given in 22.

In this algorithm, the controller monitors the terminal voltage of BWIG continuously and is compared with the reference voltage. Modulation index is changed in steps according to the magnitude and sign of error voltage. it was observed that the maximum variation in the output voltage was within the limit of 10%.

VII. CONCLUSION

A novel generator with its inherent capability of producing constant frequency three phases sinusoidal voltage under varying speed conditions of the prime mover has been presented in this paper flux analysis is carried out using Ansys Maxwell software indicates that the machine has flux distribution different from that of a conventional induction machine. A comparative study of the performance of BWIG and TSCAOI configurations shows better efficiency and controllability of active power in both stand-alone and grid-tied configurations. Hardware implementation results of the

closed-loop control operation of BWIG are indicative that it is an ideal solution for wind energy generation applications. The laboratory prototype is developed from an existing induction machine for experimental purpose. A study is conducted to find out the cost of a real size generators for practical use. The manufacturing process of a new machine might be costly compared to existing configurations. But as per the opinion of manufacturers, bulk production of the same will reduce the cost significantly.

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V. PREMA (Senior Member, IEEE) was born in Thiruvananthapuram, Kerala, India, in 1979. She received the B.Tech. degree in electrical engineering and power electronics from Calicut University, in 2001, and the M.Tech. degree in electrical engineering and power electronics and the Ph.D. degree in electrical engineering from Visvesvaraya Technological University, in 2005 and 2018, respectively. She has 16 years of teaching and industry experience. She is currently working as an Associate Professor with the B.M.S. College of Engineering, Bengaluru. She has authored more than 25 articles in various journals and conferences. Her research interests include renewable energy, forecasting, and power electronics.

M. S. BHASKAR (Senior Member, IEEE) received the bachelor's degree in electronics and telecommunication engineering from the University of Mumbai, Mumbai, India, in 2011, the master's degree in power electronics and drives from the Vellore Institute of Technology (VIT) University, India, in 2014, and the Ph.D. degree in electrical and electronic engineering from the University of Johannesburg, South Africa, in 2019. He worked as a Research Student with the Power Quality Research Group, Department of Electrical Power Engineering, Universiti Tenaga Nasional (UNITEN), Kuala Lumpur, Malaysia, in August/September 2017. He worked as a Research Assistant with the Department of Electrical Engineering, Qatar University, Doha, Qatar, from 2018 to 2019. He was a Postdoctoral Researcher with his Ph.D. Tutor at the Department of Energy Technology, Aalborg University, Esbjerg, Denmark, in 2019. He is currently with the Renewable Energy Laboratory, Department of Communications and Networks Engineering, College of Engineering, Prince Sultan University, Riyadh, Saudi Arabia. He has authored 150 plus scientific papers with particular reference to DC/DC and DC/AC converter and high gain converter. He is a Senior Member of IEEE Industrial Electronics Society, IEEE Power Electronics Society, IEEE Industry Applications Society, IEEE Power and Energy Society, IEEE Robotics and Automation Society, IEEE Vehicular Technology Society, IEEE Young Professionals, and various IEEE councils and technical communities. He received the Best Paper Research Paper Awards from IEEE-GPECOM'20, IEEE-CENCON'19, IEEE-ICCPCT'14, and IET-CEAT'16. He received the IEEE Access Award "Reviewer of Month," in January 2019, for his valuable and thorough feedback on manuscripts and for his quick turnaround on reviews. He is an Associate Editor of *IET Power Electronics* and a Topic Editor of *Electronics* (MDPI), Switzerland. He is a reviewer member of various international journals and conferences, including IEEE and IET.

P. MEENA (Member, IEEE) was born in March 1964. She received the B.E. degree in electrical engineering and the M.E. degree in power electronics from Bangalore University and the Ph.D. degree in electrical engineering from Visvesvaraya Technological University, in 2018. She was a Professor and the Head of the Department of Electrical and Electronics Engineering, B.M.S. College of Engineering, till April 2021. She has 33 years of teaching experience. She has authored more than 25 articles in various journals and conferences. Her research interests include DSP applications to power quality improvement and power control strategies in renewable energy applications and education.

DHAFER ALMAKHLES (Senior Member, IEEE) received the B.E. degree in electrical engineering from the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, in 2006, and the master's (Hons.) and Ph.D. degrees from The University of Auckland, New Zealand, in 2011 and 2016, respectively. Since 2016, he has been with Prince Sultan University, Saudi Arabia. He is the Leader of the Renewable Energy Research Team and Laboratory. His research interests include power electronics, control theory, unmanned aerial vehicles, renewable energy systems, and FPGA applications.

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