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Evaluation of Polyphase and Multi Winding Induction Machine: A Review

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ABSTRACT

The Dual Stator Windings Induction Motor (DSWIM) is an innovative motor technology that become increasingly popular in recent years. The major advantages are the ability to operate at a higher power density, more efficient operation, higher output power, and improved mechanical torque.This article presents a study on multi winding induction machine whether it is a dual stator, a twin stator, or a multi-phase induction machine regarding improved design, analysis, modeling, simulation, and testing prototype. DSWIM design requires only modification to the frame design of a single stator machine. Unlike the twin stator model which is more complex manufacturing, complicated assembly processes, and increased overall cost of the machine.Finite Element Analysis (FEA), vector control, and equivalent circuit analysis, techniques are used to analyze and simulate DSWIM under various operating conditions and to optimize the machine design for specific applications.The optimal phase shift angle between the two stator windings of DSWIM is 30° and it relies on a number of variables, including the machine's design, operating environment, and its intended use.

Keywords:

DSWIM, Twin Stator, Power and control Windings, FEA, multi-phase, DWIG.

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1. INTRODUCTION

Early publications in the 1900s, mentioned the use of dual stator winding machines. dual stator winding sets provide flexibility in energy conversion as work in motoring or generating applications [1]. For instance, energy transmission between stator winding sets is possibility in addition to energy transfer between stator and rotor, as is the case in single winding machines.

Wound rotor induction machine, which is classified as the oldest dual winding machine in recorded history. The stator and rotor windings of this kind have the same number of poles and phases, and the rotor winding is always called the secondary winding. The ability of this machine to maintain a constant output frequency at variable rotor speeds is one of its most notable benefits. Also it has the ability to send the rotor slip energy back to the system help to improves the efficiency of the whole system [2].

From the point of view of the stator winding, Dual winding machines have been divided into two categories based on how the stator is wound: split-wound and self-cascaded [3].

The split-wound dual winding machine, which was developed in the 1920s to boost the output capacity of high power synchronous generators [4]. The split-wound synchronous machine features two identical but independent three-phase winding sets wound for the same number of poles, depending on whether the rotor is round or salient [5].

The squirrel-cage machine version also features two three-phase stator winding sets with the same pole number that are symmetrical and independent [6]. When the winding sets linked together resulting in significant circulating currents in the presence of unavoidable unbalances in the supply voltages [7].

In 1907. “Hunt” introduced the "self-cascaded machine," which is now known as the brushless doubly-fed machine (BDFM). It contains two stator winding sets, each with a different number of poles but the same overall number of phases and the same stator core [8]. To include the effects of cascade connection, a specific rotor construction with nested loops is needed as shown in Fig. 1 [9]. Brushless doubly-fed machines can be further subdivided into brushless doubly-fed induction machines and brushless doubly-fed synchronous reluctance machines due to the various rotor structures [6]. Although the efficiency of the machine is rather low due to the unusual rotor construction, it may be useful in driving applications with a limited speed range.

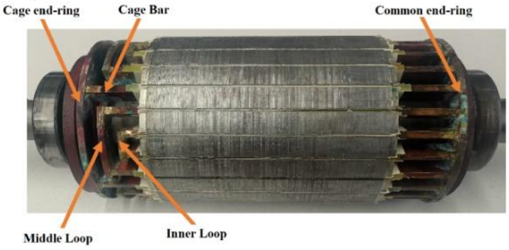

Figure 1: Nested Loop Rotor Structure of Induction Motor **[9].**

The last one is the most modern dual stator winding squirrel-cage induction machine. It has simple sensor-less control (particularly at low speeds), excellent dependability, and no circulating currents **[10].** Also It has a typical squirrel-cage rotor and a two stators winding sets with various numbers of poles (P_1 and P_2, such as 2/6 or 4/12) **[11].** Any combination of various pole numbers might theoretically be utilized, but The most favorable layout should have a pole ratio of 1:3 **[12],** to prevent localized saturation, and reduce stator losses. The machine costs less since a common squirrel cage rotor is used. Simple construction, easy connections, robustness under severe operating conditions, cheap cost, and little maintenance are all advantages.

2. DUAL STATOR INDUCTION MACHINE OPERATION PRINCIPLE:

Induction machines are utilized in practice to consume a sizeable portion of the total energy produced. As a result, the machine's performance improvement become necessary for cost-effective system operation overall **[13].**

Low power factor and inefficient operation are the results of design mistakes in induction motors. This creates the opportunity for superior design abilities, and dual stator winding is one of the best options. These two windings may be fed either by different voltages and same frequency or by variable voltages and variable frequencies. The interaction between the two magnetizing fluxes generated by the two windings determines the resultant flux, which can be altered to suit the necessary operating circumstances. In general, the following factors determine the operating conditions **[14]:**

1) The torque-speed characteristic's nature.
2) machine efficiency.
3) power factor.
4) System harmonic components.

In DSIM, the stator frame holds two windings that may be identical or different in terms of turn count, conductor size, current carrying capability, and number of poles. Fig. 2 provides a comprehensive explanation of the DSIM concept **[15].**

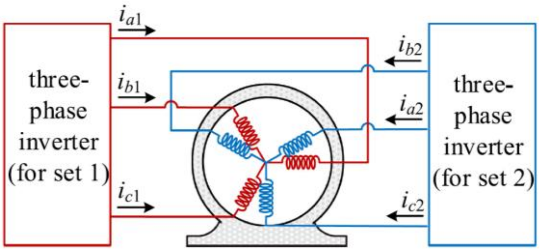

Figure 2: concept of dual stator induction machine **[15].**

When one of the stator windings in a DSIM system is fed with rated voltage and frequency while the other is fed with variable voltage, the arrangement regulates the machine's speed and torque over wide range. The DSIM functions as two distinct induction machines physically connected to the same shaft due to the decoupling effect created by differing stator windings. all control methods used for induction motor drives are also applicable in DSIM **[16].**

The control strategy is to produce two distinct (additive or subtractive) torque components so that the produced torque-speed characteristic satisfies the demands of a particular application **[17].** Unlike traditional speed control techniques, DSIM gives users the freedom to adjust the motor's resulting torque-speed characteristic. Rotor frequency is no longer determined by mechanical speed, where [N_r = (120×f/P) × (1-S)], where **f** is supply frequency, **P** is no. of pole pairs, and **S** is slip factor. Therefore, unlike the conventional induction motor, there is no direct relationship between speed and the supply frequency, Therefore, zero supply frequency does not lead to zero speed **[18].**

Without impairing Induction motor positive qualities (cost, reliability, robustness) and performance, DSIM offers a speed control that is smoother than that offered by a normal induction machine. Industrial requirements are met by dual stator windings with different numbers of poles which share the same machine core. The two stator windings are no longer magnetically coupled, and the torques generated by each of them are likewise decoupled **[19].**

The difference in pole counts causes a decoupling effect, which makes the DSIM behave as two separate conventional induction machines connected to the same shaft. Due to complete electrical isolation between the two stator windings, it’s possible to respond dynamically quickly **[20].**

Power is either delivered to the two windings by two 3-phase auto transformers or by two VSIs, offering separately controllable torques that can be combined to produce desired results. DSIM have Numerous benefit like **[21, 22]:**

1. speed sensor-less operation.
2. enhanced dependability.
3. More freedom in adjusting the motor's resulting torque-speed curve.
4. zero speed operation is achieved by individually regulating the currents of the two stators. Therefore, regardless of the mechanical speed, a minimum electrical frequency is maintained. The purpose of this feature is to reduce the detrimental effects of stator resistance during low-speed operation.

3. DUAL STATOR INDUCTION MACHINE OPERATION MODES:

In DSIM, two distinct operating modes are taken into account. They are synchronous and asynchronous operating modes:

3.1 Synchronous Operating Mode:

In Synchronous Operating Mode, the two stators of the DSIM are excited by two separate supplies that are synchronized. This allows the motor to operate in a synchronous manner, with both stators providing synchronous rotating fields, resulting in a smoother and more efficient operation. The synchronous operating mode also enables the motor to operate at a constant speed, which is useful for various industrial applications **[23, 24].**

In other words, the frequencies fed to the two stator windings in this mode are fed in a 1:3 ($F_1/F_2=P_1/P_2$) ratio, the same ratio as the number of poles. As a result, supply voltages are adjusted to manage torque. Due to the fact that the produced torques are additive and in the same direction, this action is appropriate for medium and high-speed applications.

3.2 Asynchronous Operating Mode:

One of the stators operates in a synchronous mode with the rotor, while the other stator operates in an asynchronous mode with the rotor. This mode allows for better control of the motor's speed and torque, as well as improved efficiency and power factor. The synchronous stator provides a fixed magnetic field that locks to the rotating magnetic field of the rotor, while the asynchronous stator provides a variable magnetic field that interacts with the rotating magnetic field, producing the desired torque and speed. This mode is commonly used in industrial applications where precise speed and torque control are required, such as in mining and metal processing.

In other words, the higher pole winding is fed with variable frequency (higher value), while the lower pole winding is fed with constant frequency at the lowest attainable value. For example, 6-pole winding is fed with a higher variable frequency, such as 50 Hz, while the 2-pole winding is fed with a minimum frequency, such as 5 Hz. As a result, the high pole winding's supply frequency and voltage govern the torque. Due to the fact that the two torques oppose one another in the asynchronous operating mode, this operation is appropriate for low speed applications.

As was previously mentioned, DSIM functions as two separate conventional induction machines that are mechanically connected to the same shaft. As a result, two distinct torques are generated, and the speed can be regulated by adjusting the two torques while keeping an electrical frequency that is at a minimum and independent of the mechanical speed. In this scenario, there is no coupling between the two stator windings, and the mutual flux linkage only exists in the corresponding stator and rotor. When one stator winding receives voltage, it is discovered that the voltage across the other winding is zero, setup like that produces no circulating currents. Only the third harmonic and its multiples could exist because the used pole ratio is 1:3. These harmonics are also removed if two stator windings are star linked with isolated neutrals.

4. LITERATURE REVIEW

The conventional motor can be made to work efficiently when coupled with power electronic circuitry that uses components like IGBTs and other similar devices; nevertheless, they have drawbacks such as harmonic production, decreased dependability, and increased cost. A Dual Stator Induction Motor (DSIM) is one of the solutions developed by inventive engineers to address these issues. For the first time, it was used for turbine alternators in 1920. DSIM is a unique instance of a multi-phase or multi-pole machine. The same magnetic circuit (stator) houses two identical stator windings that are electrically isolated and share the same squirrel cage rotor. Different tactics, such as different connections of stator windings (star/delta, star/star, delta/star, delta/delta), and use of different controlling techniques, are frequently used for Dual winding induction machine **[25].** For the purpose of this review paper, Fig. 3 shows the general categories that have been used to group DSIM-related literature:

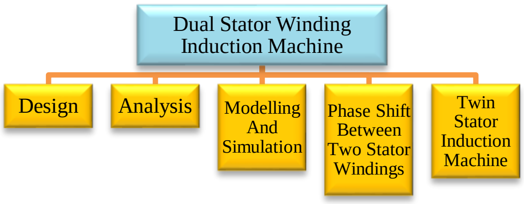

Figure 3: DSIM related literature Categories.

4.1 Dual Stator Induction Machine Design:

The induction machine is one of the earliest and most extensively used machines, have been produced for a long time. The induction machine design techniques are very mature. Fortunately, some of the machine design methodologies for an induction machine can be applied to design process of the dual stator winding induction machine under examination because it shares some characteristics with the typical single winding induction machine.

H. Keshtkar **[26],** an improved design of a dual stator winding induction generator (DSWIG) with a typical squirrel cage rotor is presented for use in wind turbines, see fig. 4. Since energy derived from renewable sources is typically quite expensive, the efficiency criteria is proposed as the objective function. In comparison to a single-winding induction machine of comparable power, the DSWIG has a larger core. The power winding (6 poles, 150Hz) frequency is also three times greater than the control winding (2 poles, 50 Hz) frequency. Therefore, reducing core losses is very important for increasing machine efficiency. The ideal parameter values are designed in the first stage, and the desired generator is then assessed using the finite-element approach, which is supported by Ansys Maxwell software. The results demonstrate that the DSWIG is significantly more efficient than before.

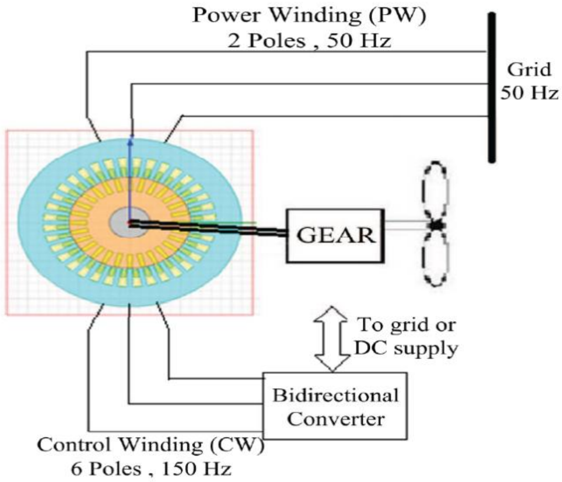

Figure 4: Operating system of DSWIG [26].

R. Resmi **[27],** a novel design of brushless doubly fed induction machine employing a delta-star connection in one of the two stator windings is suggested, to lessen the torque ripples. The new 3.7 KW brushless double fed induction machine prototype has been created and put through testing in a lab. Brushless double fed induction machines have undergone tests in both synchronous and asynchronous modes. In asynchronous driving mode, simple induction and cascade connections have been tested. Synchronous mode testing has been conducted under both generating and motoring situations.

According to test results, the new brushless doubly fed induction machine not only possesses the qualities needed for a wind turbine generator but also has the capacity for applications requiring variable torque-variable speed motors as well as constant speed applications.

Khoshhava **[28],** proposes an ideal design method for DSWIMs that maximizes the benefits of DSWIMs while minimizing the distortion of stator current. In this regard, the best pole pair ratio and the ideal flux levels ratio of winding sets are first found. The benefits of DSWIM, particularly the capability of operation in the zero speed region, are then defined to have maximum output power while using the same stator and rotor frames. Based on the suggested methodology and utilizing widely accessible standard stator and rotor frames from the marketplace, a DSWIM is built, simulated in ANSYS/MAXWELL, and constructed. Experimental evaluations confirm that the rate of minimizing the distortion has been improved 19% when compared to traditional DSWIMs.

For high-power induction motor drives Hatua and Ranganathan **[29],** suggested a brand-new configuration of dual three-phase stator windings (called Active Reactive Induction Motor

–ARIM) as shown in fig.5. One winding is intended to handle the primary (active) power and is built for higher voltage. The second winding, which is intended to transport the excitation (reactive) power, is built for lower voltage.

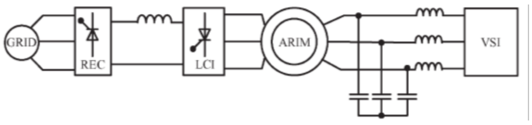

Figure 5: Proposed ARIM drive by Hatua and Ranganathan **[29]**.

A voltage source inverter with an output filter that is based on insulated-gate bipolar transistors powers the excitation winding. A current source inverter with load commutation feeds the power winding. By pumping the necessary leading reactive power from the excitation inverter, the thyristors in the load-commutated inverter (LCI) are commutated. In order to ensure that the machine's electromagnetic torque is smooth, the MMF harmonics caused by the LCI current are additionally wiped out by injecting a sufficient compensating component from the excitation inverter. The notion is illustrated through the results of a prototype drive.

[30], and **[31]** discuss the application of the 6 phase/3 phase Dual Stator Winding Induction Generator (DSIG) in the wind power generation system as shown in Fig. 6. In order to reduce the capacity of the static excitation controller, the value of the capacitor utilized in the excitation circuit is optimized based on machine specifications, loading, and speed range. A decoupling control approach is investigated through simulations and tests. The outcomes of the simulation are used to verify experimental findings. The design and system optimization presented in this study, are particularly relevant to wind power systems.

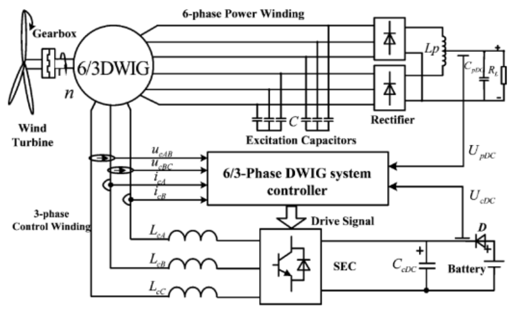

Figure 6: DWIG wind power system, the first stator winding (power Winding) consist of is 6-phase winding, the second stator winding (control Winding) consist of is 3-phase winding. **[30].**

Munoz and Lipo **[32]** discuss and create a prototype of induction machine consists of a standard squirrel-cage rotor and a stator with two separate windings wound for a dissimilar number of poles 4:12. Each stator winding is fed from an independent variable-frequency Variable voltage inverter as shown in fig. 7. and a digital signal processor (DSP) is used to manage speed.

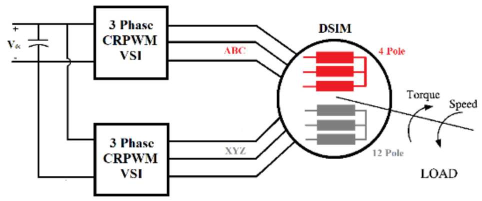

Figure 7: Dual stator induction machine drive. Each stator winding is fed from an independent carrier-redistribution pulse width modelation (CRPWM) inverter **[32]**.

The proposed drive offers such advantages as better reliability, and more flexibility to manipulate the resultant torque-speed curve of the motor. Also, zero-speed operation is achieved by independently controlling the two sets of stator currents, hence, maintaining a minimum electrical frequency of about 0.5 Hz independent of the mechanical speed. The proposed drive is a speed sensor less operation (uses less electrical circuitry), which reduces harmonics and allows for smooth speed control from zero to rated speed without overheating.

Hadiouche et al. **[33]** discuss the harmful harmonic that occurs when DSIM is supplied by VSI. These harmonic currents in the stator windings increase the losses that lead to the machine overheating. he modeled and designed dual-stator winding ac machines for safe operation with VSI. A new reference frame model for DSIM is put out that takes mutual leakage coupling into account. The circulating harmonic currents that were stated earlier can be highlighted using this model. According to research, the leakage inductance connected to these harmonics has a very low value and is strongly influenced by coil pitch. Also demonstrated have the necessity of full pitch and the need to study unique slot shape designs in order to restrict the amount of circulating currents. An experimental study using a DSIM prototype is provided, and the results demonstrate a strong connection between the experimental data and theoretical curves.

Ming Cheng **[34],** For EV/HEV applications, a novel dual-stator brushless doubly-fed induction motor DSBDFIM is presented. The suggested configuration shows remarkable potential as a traction motor in EV/HEVs thanks to its benefits of high torque density, wide torque-speed range, synchronous motor-like properties, robust rotor configuration, and low cost as a result of the absence of permanent magnets. Discussions focus on the potential architecture see Fig. 8, rotor winding connection is separated for each stator, the outr rotor characteristics related to outer stator, the inner rotor characteristec related to inner stator. both rotors are linked mechanically by non megnatic support material. Both the outer and inner stator windings are connected to the battery package through a 3- phase inverter, which allows the bi-directional power flow. and variable speed capability. Finite element analysis (FEA) is used to show the electromagnetic properties of a prototype machine. An equivalent experiment confirms the viability.

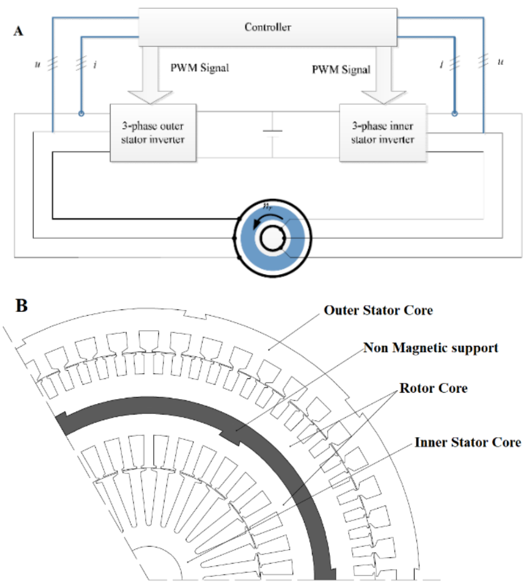

Fig. 8: Dual Stator Brushless Doubly-Fed Induction Motor model. A) drive system consest of twe PWM inverter for each stator. B) The cross section of the DSBDFIM shows the outer and inner stator and the rotor structure between them **[34]**.

In order to create a high-power, seven-phase induction motor suitable for variable-speed applications, Heidari et al. **[35]** attempts to build an ideal electromagnetic-thermal design approach. The optimal design procedure can be performed considering different objectives and constraints. The design stage is subject to limitations in technical and economic terms. Basically, the design procedure involves determination of geometries and dimensions of different parts, weight, material characteristics, output parameters, and operation characteristics under international standards. Important design parameters include high effciency, low weight, low cost, desired power factor, and low temperature rise. The traditional design method can be effectively used at the initial design stage. The fowchart of the traditional design of induction motor is illustrated in Fig. 9, the objective function is designed to maximize efficiency, power factor, power-to-weight ratio, starting torque, and starting current. Additionally, the electrical, mechanical, dimensional, magnetic, and thermal constraints are taken into account in this optimization study to guarantee that the intended machine can actually be built. The current displacement phenomena are taken into account while calculating the rotor parameters, while the coupled-circuit method is used for nonlinear electromagnetic modeling. At each iteration of the optimization research, a lumped-parameter-thermal model is created to calculate the heat increases of various sections. Finally, the ideal 1-MW 4-pole motor's performance parameters are verified based on 2D FEA analysis.

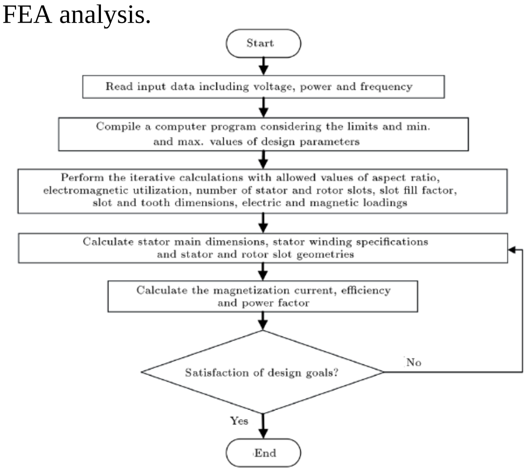

Figure 9: Flowchart of the induction motor design **[35]**.

Five-phase squirrel cage induction motors (FSCIM) have higher power densities, flexible control strategies, fault-tolerant operation, and lower torque ripple than conventional induction motors. These features have made them popular for use in electrical vehicles, rail transit, underwater vehicles, and other applications. The analytical design optimization technique described by Chen **[36],** is based on the integration of the differential evolution algorithm (DEA) and the electromagnetic equivalent circuit (EEC). Additionally, the impact of harmonic specific leakage permeance on three- and five-phase winding is thoroughly explored. Analytical models are used to assess the nonlinear effects of design geometrical factors (slot openings, main dimension ratio, yoke height, airgap length, etc.) on the performance of the fundamental FSCIM model. The iron core saturation, rotor slot skew width, stator end winding, slot leakage inductance, and stator and rotor slot structural harmonic characteristics are taken into account for more precise results. As the entire objective function, FSCIM's efficiency, power factor, maximum torque, slot fill factor, and material consumption are calculated. The proposed optimum model's accuracy is confirmed by the transient finite element analysis (TFEA) and experimental test. Additionally, TFEA confirms the viability of the multi-objective optimization design strategy offered by the analytical model.

There are very limited literatures involve using the multi-objective optimization technique to design the DSWIM. Taking objectives (maximum power factor, maximum efficiency, maximum locked rotor torque, minimum locked rotor current and minimum active material) in fresh design, it is not possible to optimize them all at once. However, one objective can be maximizing without excessively prejudice others. because it helps the designer of DSWIM to find a good compromise between the conflicting objectives.

4.2 Dual Stator Induction Machine Analysis:

From the perspective of DSWIM analysis, the measurement of air gap flux densities is one of the fundamental distinctions between a dual stator winding induction machine and a standard induction machine. The standard approach, which takes into account only one air gap flux linkage, is inapplicable since the dual stator winding induction machine's air gap flux linkage has two distinct components, each of which has its own frequencies, magnitudes, and phase angles.

When the dual stator winding machines are operating under various loads, the challenge is figuring out how to prevent the deep saturation issue. The solutions lie in developing an appropriate method for assessing the flux density for the dual stator-winding machine and analyzing the flux density for each stator winding.

Pienkowski **[37]** compares and contrasts two methods for DSIM mathematical modeling. The first method assumes that the machine consists of two independent 3-phase induction motors that are mechanically linked, the mathematical model examines the analysis of asymmetric electromagnetic motor characteristics.

In the second strategy, the machine is treated as a six-phase induction machine (multi-phase machine). Only two stator windings that are identical can be used in this method. The mathematical modeling is done in phase variable form for both strategies. The two models are used to analyze DSIM. The author demonstrates how the fundamental control techniques can be used with DSIM. They are (i) scalar, specifically Direct Torque Control (DTC), which enables decoupled control of electromagnetic torque and stator flux. (ii) Indirect Field Control (IFOC) to achieve decoupled control on electromagnetic torque and rotor flux. The investigation by the author also shows that, when compared to the second strategy, the first approach is more complicated and needs more signal processing and management. Thus, the author asserts that the proposed method is preferable than the current methods. The torque responds to reference signals from the DTC more quickly using the suggested way. Simulation on a 4 kW DSIM prototype serves as a demonstration of this. A phase coordinate system is used to formulate the mathematical model created for DSIM.

According to Tamrakar and Malik model **[38],** adding a second winding to the stator of a three-phase induction machine improved its power factor, see Fig. 10. Additionally, a method is created for determining the ideal power factor value for the greatest performance. Results from experiments and computer simulations demonstrate that the plan produces virtually sinusoidal current with almost zero harmonics in the PWM output.

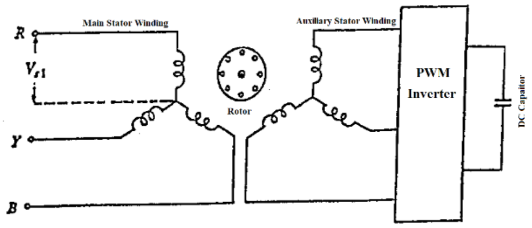

Figure 10: Schematic diagram of the proposed scheme **[38]**.

Saptarshi Basak [39]**,** The dual stator winding induction generator's (DSWIG) stator has two distributed windings implanted within it, while the rotor has a squirrel-cage design. One of the windings is connected to an unregulated rectifier, while the other to a PWM converter with a fractional rating, see fig. 11. Within the generation system, an uncontrolled rectifier reduces the quality of the power. Additionally, as induction generators are loaded, the demand for reactive power rises. This work focuses on the design and operation of a freestanding DSWIG-based dc system, where the voltage regulation and power quality problems are solved by combining a series capacitor and a passive tuned filter. To show the efficacy of the suggested alternative, simulation results using MATLAB/Simulink and experimental findings (obtained from a laboratory prototype) shows that Doubly-fed induction generators are appropriate for systems with a constrained speed range since the overall control can be accomplished by fractionally-rated converters.

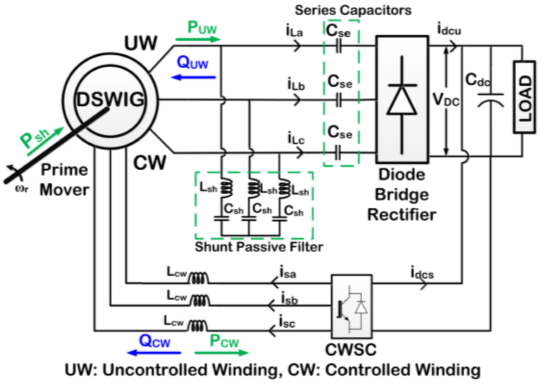

Figure 11: Proposed configuration of a standalone dc generating system based on DSWIG (with tuned passive filters and series capacitance) **[39]**.

Bojoi et al. [40] compare various digital PWM approaches and evaluate the benefits and drawbacks of each one. The cost of the hardware and software required in the DSP platform, the difficulty of implementation, and the harmonic injection are used to compare the digital PWM techniques for DSIM. Space vector modulation (SVM), vector space decomposition, vector classification, and zero-sequence injection approaches are the strategies that are taken into consideration. The paper offers a comparison of the performances brought on by several strategies, including two that the authors introduce. The vector classification and double zero-sequence injection strategies are proven to produce superior results than the space vector decomposition and SVM techniques with regard to minimizing harmonics and straightforward implementation.

Chandrasekaran and Manigandan [41]**,** discuss the DSIM's design for a high efficiency and good power factor, compared to a standard induction motor, throughout a wide speed range. A 3 kW, 4 pole, 415 V, 1440 rpm DSIM is developed, constructed, and tested to achieve this goal. The DSIM is shown to have a greater slot fullness factor (43.3%), allowing for better slot use. The prototype has two different working modes: power balancing mode and efficiency maximization mode. One of the stator windings is supplied by a three-phase source, whereas the other stator winding is electrically loaded. A capacitor is also placed to improve efficiency and power factor. The authors claim that a device like this is useful in industries like textile manufacture, when one winding is fed while the other supplies the lighting loads. Also, said to have enhanced efficiency are the experimental results.

Soman [42]**,** [43] presented a detailed analysis of the DSIM performance. With DC bus shared.

Each stator is fed by a variable frequenc y variable voltage inverter. First, each stator winding tested for no load and blocked rotor, and the results used to draw circle diagrams for each stator in order to determine the various motor parameters. Next, load tests are conducted simultaneously and simultaneously on the two stators, and torque speed curves are plotted for both configurations. In [44] having the stator's winding structured in such a way that the speed can be varied by appropriately switching the number of poles allows for the option of having more than one speed. means by creating a twin stator winding. In [45] Examine how the performance of a (4 and 12 pole) three phase, dual stator winding induction motor is affected by changing supply voltages. For the machine with only one excited stator winding (4 poles excited alone, then 12 poles excited alone), experimental analysis is performed. The results demonstrate that we can adjust the torque produced by the motor while maintaining the same speed by changing the voltage at the two stator winding connections. Additionally, it is feasible to alter the motor's working speed while maintaining the same torque.

Bu et al. [46], examine the need for auxiliary excitation capacitors and filter inductances in DSIG variable frequency AC generating systems, see fig. 12. With the right amounts of the auxiliary excitation capacitor and filter inductance, static excitation converter capacity and static performance of the output voltage can be enhanced. Experimental findings are offered for validation, and design approaches for this choice are developed.

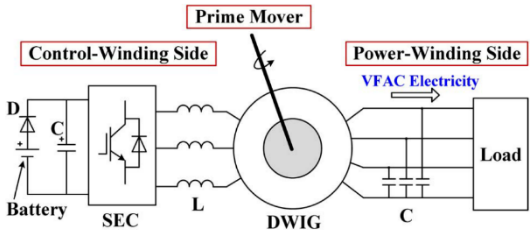

Figure 12: Diagram of the DWIG VFAC generating system **[46]**.

Haussman et al. [47]**,** [48]**,** presents a technique for a dual stator induction machine (DSIM) characterization. It combines a novel technique for DSIM parameter identification with the known technique for three-phase machine characterization. Application of the traditional three phase machine characterization to DSIMs is also possible, but it necessitates making an assumption about the leakage distribution between the stator and rotor. Rotor and stator leakage inductances are typically believed to be equal. No such premise is necessary for the procedure presented here. Stator and rotor parameters can be measured separately instead of only as a combined total, as in three phase machines. This is accomplished by operating the machine in blocking or idle mode while using an unbalanced current split between the two stator systems. While in blocking mode, the rotor leakage inductance and rotor resistor are recognized, the main inductance can be measured in idle mode. In any operating point, the stator resistor and stator leakage inductance can be determined. There is no longer a need for a DC measurement. This method produces a DSIM model with precise parameters that is more accurate. A thorough characterization of a prototype machine demonstrates this. It demonstrates how stator and rotor leakage inductances vary by a significant amount. The stator leakage inductance appears to be dependent on the operating point as well.

Bojoi, and Boglietti et al. [49], [50], [51] proposes a performance evaluation of three-phase and dual three-phase induction Pulse Width Modulation (PWM) inverter fed motor drives, see fig. 13. The effectiveness of dual-three phase machines as compared to their three phase equivalents is the main focus. A dual three phase machine with two sets of stator three-phase windings that are spatially offset by 30 electrical degrees (an asymmetrical six-phase winding arrangement) has been tested for both three-phase and six-phase winding configurations under the same magnetic conditions. The efficiency performance of three-phase and dual three-phase induction motor drives with PWM Voltage-Source Inverters (VSI) is evaluated using simulation and experimental results.

FEM is a numerical method that can be used to solve complex electromagnetic problems related to the DSIM, such as electromagnetic field distribution, magnetic flux density, and performance characteristics. But we can use another technique of analytical models, which are derived from the principles of electromagnetic theory. These models are used to predict the performance of the DSIM, such as speed-torque characteristics, efficiency, and power factor.

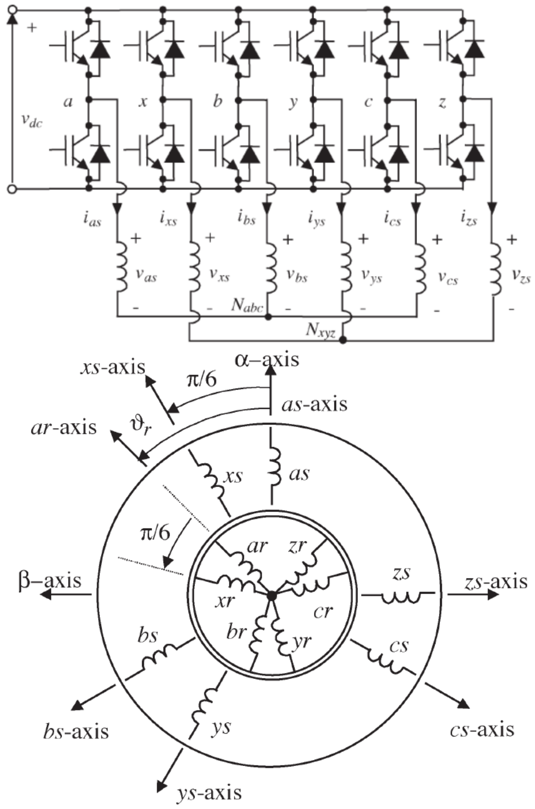

Figure 13: PWM Inverter fed dual three phase induction machine **[49]**.

4.3 Dual Stator Induction Machine Modelling and Simulation:

It is generally known that the standard q-d model of an ac machine makes the fundamental assumption that the stator windings are dispersed sinusoidally all over the stator surface. The control and fundamental component dynamic and steady state analyses of the machine can be performed using machine models based on this supposition in most cases. The typical q-d model, however, is insufficient if the study's main objectives are to determine the impact of high order harmonic MMFs on machine performance, analyze fault conditions, examine performance when rotor eccentricity is present, or examine a general machine with variable winding connections. A generic machine analysis requires a model based on the machine geometry and winding configurations of an arbitrary n-phase machine.

Khoudimi et al. [52] describe the 4.5 kW, 220 V, 2 pole, 50 Hz, space vector modeling method used by the DSIM. Regular PI controllers are used to field control the machine by adjusting the stator currents. In this instance, the machine's dynamic performance is deemed to be good. The Indirect Field Oriented Control (IFOC) of DSIM simulation results demonstrate good dynamic performance without the necessity for flux measurement. It has been demonstrated that the suggested indirect vector control method with PI controller produces effective outcomes.

When DSIM is fed via VSI, the inevitable creation of harmonics causes additional losses and machine overheating. Hadiouche et al. cover this in their discussion [53]**.** With eight poles and a 15-kW rating, the suggested DSIM model considers the performance impacts of coil pitch and mutual leakage coupling. For 48 stator coils, 96 terminals are brought onto the terminal box in order to accommodate the various winding connections and coil pitches. For safe operation of DSIM with VSI, the authors assert that in order to eliminate circulating harmonic currents and space harmonics in air gap flux, full pitch coils and unique slot designs are necessary.

Rabiaa et al. [54] study the impact of stator mutual leakage inductance on the modeling of DSIM in steady state and dynamic operation. Two alternative models are taken into consideration for this analysis. One of the models takes into account mutual inductance, whilst the other model ignores it. According to simulation results, stator mutual leakage reactance must be taken into account in order to obtain precise results during transient operation.

A generalized d-q axis model for an n-phase induction motor is presented by Renukadevi et al. [55] The Simpower system block set in the MATLAB / Simulink software was used to simulate a 5, 6, 7, 9, and 12-phase induction motor, and the results are evaluated. Studies using simulations show that when the load increases, the rotor's speed decreases and its current draw rises. For various load scenarios, oscillations in torque and speed are observed in a transient condition. The transient response of multi-phase induction motors is addressed for various numbers of phases. It has been shown that even with one or two missing stator windings, a five-phase induction motor can still start and function.

By synchronizing the flux in both stator windings, the torque to current ratio of the DSIM can be increased to its maximum. Guerrero and Ojo [56] explore these circumstances in their discussion of the proper resultant flux. They also stress the importance of avoiding the saturation of the air gap in the DSIM by independently managing the fluxes of the two stator windings. The inverter control method is thoroughly defined, and its limits are also covered, in order to place both winding fluxes in the ideal location (minimizing total air gap flux). Experimental and simulation findings are used to examine the scheme's efficacy.

Ogunjuyigbe et al [57]**,** The DSIM with squirrel-cage rotor has modeling and simulation demonstrated using complex vector method's. the winding distributions of the stator as shown in fig. 14. The the first stator (ABC Coil distribution of 2 poles in the stator slots), and the second stator (XYZ coil distribution of 6 poles in the stator slots). thats mean each stator slots contents 2 layers (one layer for stator 1 coil and the other layer for stator 2 coil). The machine's performance is evaluated both with and without a load. Two sets of input conditions were used to analyze the machine's dynamic performance; in the first, both stator windings were motoring, and in the second, one winding was motoring and the other was generating. The straightforward presentation of a step-by-step process for the MATLAB-Simulink model should improve understanding of the use of complex vectors in the modeling and simulation of electrical machines. The precision and reliability of the results are confirmed by the consistency between the results in this work and those in [58]**.** This study's methodology is easily adaptable to other kinds and arrangements of electric machines and drives.

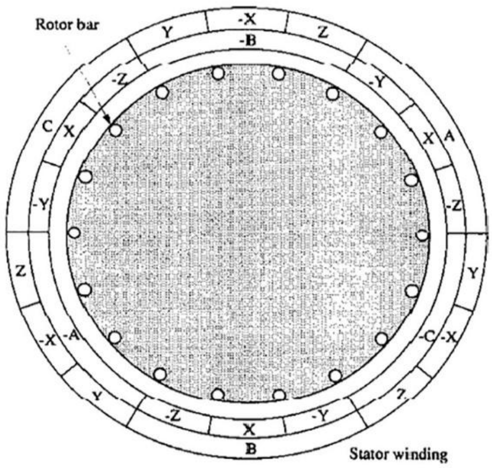

Figure 14: Dual Stator Winding Distributions **[57].**

Gregor et al. devised a test-setup for comparing several control strategies for DSIM [59]**.** The configuration is helpful for evaluating different multi-phase drives for electric vehicle applications. Specific issues, such as asymmetry in systems, voltage dips in applications requiring low voltage for operating drive, systems with high sensitivity for dead time effects, etc., can be solved by studying and analyzing the setup. As a result, the test rig can be a versatile and quick development tool for researching sensor-less applications and control strategies for different drives. A testing set up for the most promising

DSIM is described in order to test multi-phase solutions, evaluate their benefits and drawbacks, and investigate potential application areas. Additionally, authors emphasize the need to investigate application areas and DSIM's electrical properties.

Marwa et al. [60] study the behaver of DSIM when supplied by an NPC multi-level inverter. The multilayer NPC inverter source has an impact on the circulating currents and voltage between the two stars of the DSIM. By lowering torque ripples and current THD, an increase in the multilayer inverter's output voltage enhances the performance of the DSIM. Reduced voltage results in lower THD, which improves energy quality by reducing torque ripples and polluted stator currents.

recently another technique developed for modeling and simulation of electrical machine this technique is the analytical modeling approach, which involves deriving equations based on the principles of electromagnetic theory to predict the performance of the machine. Analytical models can be used to determine the speed-torque characteristics, efficiency, and power factor of the DSIM. Additionally, machine learning techniques can also be used to model and simulate DSIMs, which involves training an algorithm to recognize patterns and make predictions based on input data. Overall, these new techniques are helping to advance the understanding of DSIMs and improve their design and performance.

Bensalem and Abdelkrim [61]**,** offers sophisticated modeling and simulation tools for IM that combine all the elements into a single environment for a shared simulation platform. In this study, the power electronic converter is designed in Ansys-Simplorer, the control scheme is built in the MATLAB/Simulink environment, and the IM is created using Ansys-Maxwell based on Finite Element Analysis (FEA). Such a framework enables coupling analysis for more realistic simulation and can be helpful for precise design. This platform is used to examine system models that have defects brought on by the breakdown of various driving components.

Here, two study instances are described. The first case deals with the consequences of a PWM inverter that is malfunctioning, and the second case deals with the effects of a short circuit involving two stator phases. A co-simulation of the global dynamic model has been suggested in order to investigate the behavior of the IM and the control drives in order to study the performance of the control drive of the IM under fault situations. The co-simulation used in this study was carried out, and the scalar control simulation results also enabled verification of the accuracy of the suggested FEM platform.

4.4 Phase Difference between Two Stator Windings of DSIM:

The phase difference between the two stator windings has a significant impact on DSIM performance. The simulation results demonstrate that the phase difference has a significant impact on torque. It has been found that a 30° electrical phase difference produces outstanding performance. This is due to the fact that a 30° phase difference eliminates the majority of air gap harmonics, significantly reducing copper losses and torque ripples.

Nelson and Krause [62] describe how the performance of DSIM is affected by changing the angle between the stator winding sets using a stationary reference frame theory , see Fig. 15. In order to increase system performance, the article focuses on choosing an optimum angular displacement between two stator windings. The stator winding sets' displacements, both symmetrical and asymmetrical, are taken into account. Proper phase difference in the winding sets can enhance machine performance, including torque-speed characteristics. This study examines the analysis of multi-phase machines having arbitrary (unsymmetrical) phase discrepancies between the stator and rotor winding sets. The 7.5-hp DSIM prototype is used for simulation.

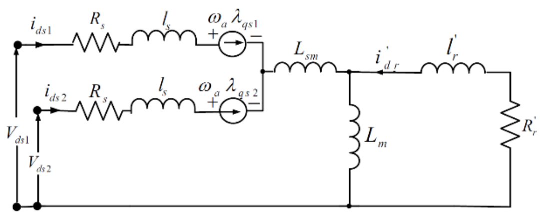

Figure 15: d-axis equivalent circuit of a DSIM in arbitrary reference frame.

By Fredj et al. [63]**,** a multi-level inverter fed DSIM is quantitatively studied while taking into account the arbitrary phase difference between the two stator winding sets. The purpose of the inquiry is to determine how a multi-level inverter's level affects the motor voltage and current total harmonic distortion (THD). The current, voltage, and torque are all impacted by the level of multi-level inverter being employed, according to simulation data. When DSIM is fed with a multi-level inverter, it is advised to limit the number of levels to no more than seven in order to deliver adequate waveforms of current, voltage, and torque.

Rehaoulia et al. [64] Talk about the DSIM stator's mutual leakage inductance's effects. The analyses of operation in steady state and transient periods are presented by the writers. The three scenarios that can occur are taken into consideration and simulated for phase differences of 30° and 0° because the two coils of the stator share the same slot space. Consideration of stator mutual leakage inductance and self-leakage inductance is one of the examples. Without taking into account the mutual leakage inductance of the stator, and without taking it into account at all. The mutual leakage inductance, according to the authors, has not been taken into account in any models previously given by other researchers. If the aforementioned parameter is ignored, the results in the transitory situation will be incorrect.

Razik et al. [65] present DSIM analysis and a mathematical model. It is demonstrated that the phase difference between the two stator windings has an impact on the machine's dynamic performance. A sophisticated steady state model is used to investigate the transient behavior of the DSIM when it is powered by a non-sinusoidal voltage. Synchronous PWM can be used to reduce the effects of greater circulating harmonic currents when feeding DSIM from VSI. Experimental results and simulation results are very similar. This leads to the conclusion that further AC machine types can be studied using the same methodology.

Again Marwa et al. [66] A d-q model of a dual stator induction motor powered by two identical PWM voltage source inverters is presented. It can be used to analyze dynamic steady operation under balanced operating conditions. The effects of shared mutual leakage inductance between the two sets of three-phase stator windings have been incorporated into the analytical model. The model was created using a general reference frame and is appropriate for analyzing machine performance when the two sets of three-phase stator windings are spatially separated by 0, 30, and 60 electrical degrees as shown in Fig. 16. The study shows a significant improvement at 30° change between the two sets. they came to the conclusion that a shift of 30° results in a decrease in torque ripples and a corresponding decrease in rotor heating. The peak stator currents per phase, however, were raised.

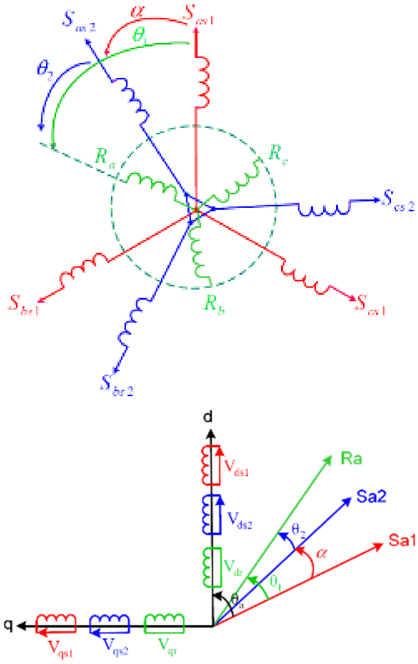

Figure 16: A) DSIM windings phase shift. B) DSIM in dq axis [66].

Alberti and Bianchi [67]**,** examine the viability of various winding connections for the same machine lamination in the design and analysis of 3-phase DSIM. Two 3-phase inverters each supply one of the two sub-windings that make up the stator winding. Therefore, the machine can run on either three or six phases (if the output of two inverters is 30° degrees out of phase). Both circumstances of load and no load are tested in the testing. Investigations into the machine's performance under different loading scenarios and at half and full capacity are conducted.

In the last two years, there have been several studies focused on the phase shift angle in Dual Stator Induction Machine (DSIM). One of the recent studies has investigated the effect of the phase shift angle on the DSIM's performance characteristics, such as torque production and power factor. The study found that by adjusting the phase shift angle, the DSIM's torque production could be improved while minimizing the reactive power requirements. Another study has proposed a new control method for DSIMs based on the phase shift angle, which involves using a model predictive control algorithm to optimize the phase shift angle to achieve the desired performance. In addition, there have been studies focused on the fault diagnosis of DSIMs based on the phase shift angle, which involves analyzing changes in the phase shift angle to detect faults in the machine. Overall, these recent studies can help to understand the impact of the phase shift angle on DSIMs and the potential benefits of controlling it for improved performance and fault detection.

The angle between the dual stator winding of an induction machine can cause more harmonic and saturation in machine core, which can lead to saturation of the machine core. In addition, the increased harmonics in the MMF can also lead to increased losses and reduced efficiency of the machine. the angle which can cause more harmonic and saturation in machine core, is the one that have the highest possible difference. Due to increase in the magneto motive force (MMF) harmonics. The best phase shift angle between two stator windings of dual stator winding induction machine depends on various factors such as the design of the machine, the operating conditions, and the intended application. Generally, a phase shift angle of around 30° is commonly used in dual stator winding induction machines to obtain the desired torque-speed characteristics and efficient power transfer.

4.5 Twin Stator Induction Machine

The Twin Separated Stator Induction Machine has two stators that are physically separated from each other. This design allows for more flexibility in controlling the motor's speed and torque. The two stators are usually connected in series or parallel to achieve specific performance characteristics.

Kaneo Takaku [68] examined The performance of a twin stator induction motor utilizing numerical calculation based on the state-space model and Runge-Kutta Gill's approach. The twin stator induction motor features two separate sets of stator windings and a high resistance end ring on the rotor, see fig 17. While the windings on one stator are fixed, the windings on the other stators can be turned. The impacts of the end ring resistance's torque and current characteristics with respect to the rotating angle are examined in terms of performance. The motor can be employed as a variable speed machine, as shown by the computer-assisted analytical results.

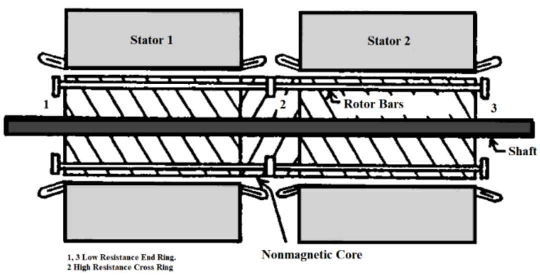

Figure 17: Twin Stator Induction Motor **[68]**.

E. Nakamae [69] presented a new squirrel-cage induction motor with variable speed that consists of a squirrel-cage rotor, two stators, and one speed-controlling stator see fig. 18. The proposed motor includes the following unique characteristics:

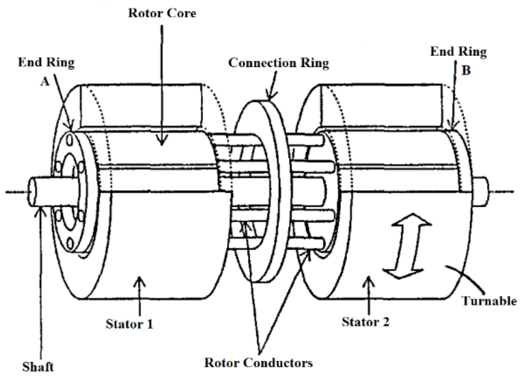

Figure 18: Structure of variable speed squirrel cage induction motor **[69]**.

- The range of speed control is extremely wide and the motoring operation is almost constant-torque under the constant supply source voltage and frequency.
- No special source like an inverter is required.
- No harmonics and low-vibration can be can be attained.
- Smooth operation from the starting to the rated speed.
- No special starter required.
- Low starting current and large starting torque.

Nagamani Chilakapati [70] Utilized a doubly fed twin stator induction motor that receives power from two separate sources with varying voltage and frequency. A pair of identical wound rotor induction motors have also been the subject of investigations. The study looks at the machine's performance capacity as well as the influence of control frequency and voltage/frequency ratio on the power needed for the control winding and the required volt ampere.

B. H. Band, & A D Ingole. [71] explains how power is distributed and flowed between the two asynchronous grids connected by the twin stator induction machine, see fig. 19. The system consests of 2 slip ring induction motors, each motor conectod to a different grid have specified voltage and frequency, the rotor terminal is connected in series through slip ring terminals, and the shafts are connected mechanically to the same load.

The technique can be used to exchange power between two asynchronous grids. without constrained by grid frequency. Because the two rotors are mechanically connected and have direct electrical connections, this system does not need slip rings. The calculated speed drives two rotors at the same speed, resulting in the same rotor frequency from either machine and rotor current devoid of harmonics. The speed is set at the estimated value, and the variation in power transferred is influenced by the two voltages, V_1 and V_2, and the angle α.

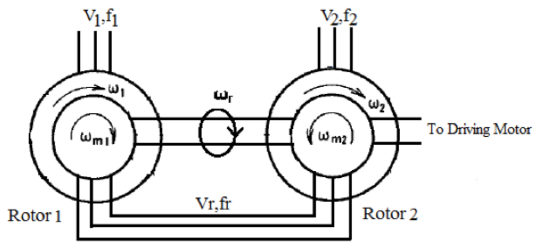

Figure 19: Power flow between cascaded induction machines **[71]**.

Alexander Pugachev [72]**,** presented an electric drive consists of two identical slipring induction motors, one of which has a rotatory stator that allows the start current to be limited. The stator and rotor circuits of the electric drive are devoid of semiconductors, but they require a more intricate mechanical mounting than industrial drives do. The experimental setup for verifying the mathematical model is provided. Results of both the Matlab simulations and the experimental research show that the main benefit of the drive under consideration is its ability to change speed over a narrow range, which lowers power losses when changing rotational angle. This drive is suitable for fans where there isn't a pressing need for transient time.

Lili Bu [73]**,** proposed a novel double-winding induction machine and its methods for speed control. The machine consists of one cage rotor and two stator windings. Both stators function as generators and motors respectively. The rotor speed can be altered by adjusting the voltage sent to the secondary or generator winding. The machine's ability to manage speed is comparable to that of a slip-ring induction motor with a rotor energy recovery system. The new machine's design, operating theory, equivalent circuit, and speed control strategies are described. The equivalent circuit is used to examine the machine's performance characteristics, and the analysis is supported by experimental results.

Ivan Subotic [15]**,** proposes a technique for precisely transferring active and reactive power between groups of three-phase induction machine windings. The number of phases in the machine must be a multiple of three (3, 6, 9, etc.), with each trio of phases denoting a single set. The first point made in the study is that the sets do not share a torque and a power in the same way. As a result, he suggests a technique that can lead to accurate power sharing. This is made possible by taking into account the entire amount of power that is transferred to or from a set via the air gap, as opposed to just the amount of power that is passed between that set and the rotor shaft. Given is a complete control algorithm for the suggested approach. Simulations and experiments validate the proposed control and theoretical concepts.

M. Sowmiya [74]**,** demonstrated a brand-new Dual Stator Multiphase Phase Induction Motor (DSMIM) setup. In order to effectively accommodate a sudden load change during acceleration, cruising, and uphill driving patterns, the proposed arrangement can be used in Electric Vehicles (EV) see fig. 20. The machine is designed using MAGNET software utilizing the Finite Element Method (FEM). Through the analysis of the flux patterns obtained at various excitation modes, the electromagnetic performance of DSMIM is examined. By examining the current, torque, and speed produced under load-driven circumstances, its electromechanical performance is examined. The article also suggests an ideology for the DSMIM production process' mechanical arrangement. To demonstrate the effectiveness of DSMIM, the simulation results are presented. With the analytical results obtained using the equivalent circuit approach, the results are contrasted and validated.

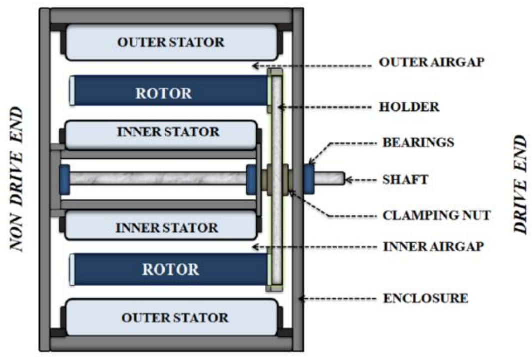

Figure 20: side view of the mechanical arrangement of DSMIM **[74]**.

The Twin Separated Stator Induction Machine disadvantages of TSSIM is that it has a more complex structure than conventional induction machines, which makes it more expensive to manufacture and maintain. Additionally, TSSIM requires specialized control algorithms to achieve optimal performance, which can be challenging to design and implement. Finally, TSSIM has a more limited power range compared to conventional induction machines, which can be a constraint in certain applications.

5. CONCLUSIONS

The benefits of the dual stator winding induction machine design make it promising option for various industrial applications.

From [13, 26, 29, 30] Adding a capacitor to one of the windings of a dual stator induction machine has various effects depending on the type of the capacitor and the specific application. It reduces the power costs, increasing power factor to more than 0.9, efficiency can also be increased by 20%, inspite of increasing motor maximum torqe to aproximatly 200%.

There are various methods for modeling and simulating dual stator winding induction machine. One of the approaches is using software programs like MATLAB and/or ANSYS to create a mathematical model of the machine. From section 4.3 we found that the choice between Ansys Maxwell and MATLAB depends on the specific requirements of your project.

If you need a comprehensive electromagnetic simulation tool with advanced 2D and 3D modeling capabilities Ansys Maxwell may be the better choice, which allows for more accurate and detailed simulations, taking into account factors such as non-linear material properties, eddy currents, and magnetic saturation. Also it dedicated algorithms and solvers are optimized for electromagnetic computations. In addition to Ansys Maxwell offers a user-friendly graphical interface tailored specifically for electromagnetic simulations, making it easier to set up and visualize your induction machine model.

However, if you prefer a versatile programming environment and already have expertise in MATLAB, it can still be a prefered option for modeling induction machines.

The angle between the dual stator winding of an induction machine can cause more harmonics and saturation of machine core. In section 4.4 it's found that 60° phase shift causes more harmonics than other angles. A phase shift angle of around 30° is commonly used in dual stator winding induction machines to obtain the desired torque-speed characteristics and efficient power transfer. Also 0° gives the same results of 30° in modeling the dual stator induction motor as given in [66]. But, in the term of THD the 30° phase shift gave the best resuls.

References [68, 69] mention Twin Separated Stator Induction Machine (TSSIM) disadvantages which are more complex structure than conventional induction machines, that makes the machine more expensive in manufacturing and maintainance. Additionally, TSSIM requires specialized control algorithms to achieve optimal performance, that is a challenge in design and implement. Finally, TSSIM has a more limited power range compared with conventional induction machines, which can be a constraint in certain applications.

The [72] gives a novel dual stator structure design, that used in switched reluctance synchrounous, and permenant magnet synchronous motor models in the resent studies.

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REFERENCES

[1] M. A. Frikha, J. Croonen, K. Deepak, Y. Benômar, M. El Baghdadi, and O. Hegazy, "Multiphase Motors and Drive Systems for Electric Vehicle Powertrains State of the Art Analysis and Future Trends", Energies, 2023, Vol.16, no.2, 768, doi: 10.3390/en16020768

[2] H. Dewi, F. H. Jufri, and C. Hudaya, "Techno-Economic Analysis of Slip Ring Motor Replaced by Standard Squirrel Cage Induction Motor with VSD," vol. 1402, Issuepp. 1–6, 2019, doi: 10.1088/1742-6596/1402/3/033107

[3] H. Guermit, K. Kouzi, and S. A. Bessedik, "Novel Design of an Optimized Synergetic Control for Dual Stator Induction Motor," vol. 38, no. 6, pp. 1828–1845, 2019, doi: https://doi.org/10.1108/COMPEL-01-2019-0042

[4] W. Cai, X. Wu, M. Zhou, Y. Liang, And Y. Wang, "Review and Development of Electric Motor Systems and Electric Powertrains for New Energy Vehicles," Automotive Innovation, Vol. 4, No. 1, Pp. 3–22, 2021, doi: 10.1007/s42154-021-00139-z

[5] M. Bagheri, E. Farjah, T. Ghanbari, "Selective Utilized Phase Number of Multiphase Induction Motors Strategy to Enhance Electric Vehicles Drive Range," 12th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC), IEEE, 2021, , doi: 10.1109/PEDSTC52094.2021.9405866.[6] P. L. Alger, E. H. Freiburghouse, and D. D. Chase, "Double Windings for Turbine Alternators," Trans. Am. Inst. Electr. Eng., vol. 49, no. 1, pp. 226–244, 1930, doi: 10.1109/T-AIEE.1930.5055483.

[7] S. S. Sivaraju, V. Chandrasekaran, "Optimum Design of Multiple Winding Induction Motor," Journal of Theoretical and Applied Information Technology, Vol. 65 No.2, pp. 467- 479 2014.

[8] L. J. Hunt, “the cascade induction motor,” Journal of Institute of Electrical Engineers, vol. 52, Issue 230, pp. 406 – 426, 1914, doi: 10.1049/jiee-1.1914.0031

[9] O. I. Olubamiwa, N. Gule, “A Review of the Advancements in the Design of Brushless Doubly Fed Machines,” Energies 2022, Vol. 15, Issue: 3, pp. 725, , doi: 10.3390/en15030725

[10] M. Y. Metwly, A. S. Abdel-Khalik, M. S. Hamad, S. Ahmed, and N. A. Elmalhy, “Multiphase Stator Winding: New Perspectives, Advanced Topologies, and Futuristic Applications,” IEEE, vol. 10, pp. 103241-103263, 2022 doi: https://doi.org/10.1109/access.2022.3209372

[11] F. Aymen, N. Mohamed, And S. Chayma, “An Improved Direct Torque Control Topology of a Double Stator Machine Using the Fuzzy Logic Controller,” Ieee Access, Vol. 9, Pp. 126400–126413, 2021, doi: https://doi.org/10.1109/ACCESS.2021.3110477

[12] Z. Wu and O. Ojo, “Modeling of A Dual Stator Winding Induction Machine Including the Effect of Main Flux Linkage Magnetic Saturation,” IEEE Transactions on Energy Conversion, Vol. 00, No. C, Pp. 465–472, 2006, doi: 10.1109/TIA.2008.926058

[13] Y. M. Oruma, L. U. Anih, Dr. J. C. Onuegbu, “Steady-State Performance of Dual Stator Winding Polyphase Induction Motor with Reactive Power Compensation”, IRE Journals, Vol. 3 Issue 8, pp. 139-146, 2020.

[14] D. F. De Souza, F. Ant, M. Salotti, I. Lu, And H. Tatizawa, “A Performance Evaluation Of Three-Phase Induction Electric,” Energies, Vol. 15, Issue 6, pp. 1–31, 2022. doi.org/10.3390/en15062002.

[15] I. Subotic, O. Dordevic, J. B. Gomm, And E. Levi, “Active and Reactive Power Sharing Between Three-Phase Winding Sets of a Multiphase Induction Machine,” Ieee Trans. Energy Convers., Vol. 34, No. 3, Pp. 1401–1410, 2019.

[16] M. A. Khlifi, “Behavior of A Dual Stator Induction Machine Fed by Neutral Point Clamped Multilevel Inverter,” Hindawi, Journal of Energy, Vol. 2018, Article ID 6968023, 2018, doi: https://doi.org/10.1155/2018/6968023

[17] H. Liu, F. Bu, W. Huang, L. Liu, Y. Hu, M. Degnano, and C. Gerada, “Control Strategy for Five-Phase Dual-Stator Winding Induction Starter / Generator System”. IEEE Transactions on Industrial Electronics, Volume: 67, Issue: 4, pp. 2607-2617, 2020) , doi: 10.1109/TIE.2019.2912767

[18] A. Soman, R. Holmukhe, And D. G. Bharadwaj, “Multispeed Operation and Testing of Dual Stator Winding Induction Machine,” international journal of scientific & technology research, Vol. 9, No. 01, pp. 3025–3028, 2020.

[19] L. N. Tutelea, S. I. Deaconu, I. Boldea, And N. Budi, “Design, Control and 2d-Fem Validation for An Double Stator Winding Induction Generator,” 39th Annual Conference of the IEEE Industrial Electronics Society, pp. 2732–2737, 2013, doi: 10.1109/IECON.2013.6699563

[20] M. A. Khlifi, “Advances and Steady-State Development of Dual Stator-Winding Induction,” IETE J. Res., Vol. 0, No. 0, pp. 2934-2940, 2020, doi: https://doi.org/10.1080/03772063.2020.1733443

[21] S. Basak, S. Member, And C. Chakraborty, “Dual Stator Winding Induction Machine: Problems, Progress, And Future Scope,” IEEE Transactions on Industrial Electronics Vol. 62, No. 7, pp. 4641–4652, 2015, doi:10.1109/TIE.2015.2409800.

[22] A. Khedher and M. Faouzi, “Sensorless-Adaptive DTC of Double Star Induction Motor,” Energy Convers. Manag., Vol. 51, No. 12, Pp. 2878–2892, 2010, doi: https://doi.org/10.1016/j.enconman.2010.06.028

[23] B. M. Chandra and A. Pradesh, “Study of Performace of Dual Stator Induction Motor,” International Journal of Computational Intelligence in Control, Vol. 13, No. 2, Pp. 729–736, 2021.

[24] R. Bogoi, F. Farina, F. Profumo, A. Tenconi, “Dual-Three Phase Induction Machine Drives Control - A Survey,” IEEJ Transactions on Industry Applications, Vol. 126, Issue 4, pp. 420–429. 2006 doi:10.1541/ieejias.126.420

[25] F. J. T. E. Ferreira, “Novel Multiflux, Three-Phase, Dual-Winding Configurations,” 2018 XIII International Conference on Electrical Machines (ICEM), Alexandroupoli, Greece, 2018, pp. 2511-2518, Doi: 10.1109/Icelmach.2018.8507066.

[26] H. Keshtkar, “Improved Design of a Dual Stator Winding Induction Generator for Wind Power Applications,” 2016 24th Iranian Conference on Electrical Engineering (ICEE), Shiraz, Iran, pp. 1278–1283, 2016, doi: 10.1109/IranianCEE.2016.7585718

[27] R. Reghu, A. V. Vidyapeetham, And V. Venkataraman, “Design and Implementation of Brushless Doubly Fed Induction Machine with New Stator Winding Configuration,” Wind Engineering Journal, Vol. 45 No.1, 2019, Doi: 10.1177/0309524x19868423.

[28] M. A. Khoshhava, H. A. Zarchi, And G. R. A. Markadeh, “Optimal Design of a Dual Stator Winding Induction Motor with Minimum Rate Reduction Level,” IEEE Transactions on Industrial Electronics Vol. 68, No. 1, pp. 1016 - 1024, 2020, Doi: 10.1109/Tie.2020.2967690.

[29] K. Hatua and V. T. Ranganathan, “A Novel Vsi- And Csi-Fed Dual Stator Induction Motor Drive Topology for Medium-Voltage Drive Applications,” IEEE Transactions on Industrial Electronics Vol. 58, No. 8, pp. 3373–3382, 2011. doi:10.1109/TIE.2010.2081958

[30] F. Bu, W. Huang, Y. Hu, And K. Shi, “An Excitation-Capacitor-Optimized Dual Stator-Winding Induction Generator with The Static Excitation Controller for Wind Power Application,” IEEE Transactions on Energy Conversion Vol. 26, No. 1, pp. 122–131, 2011. doi:10.1109/TEC.2010.2072509.

[31] V. Chandrasekaran, T. Manigandan “Double Winding induction motor- an approach for improvement of Power Factor and Efficiency,” European Journal of Scientific Research, Vol. 66, No. 2, pp.262-273, 2011.

[32] A. R. Muñoz and T. A. Lipo, “Dual Stator Winding Induction Machine Drive,” IEEE Transactions on Industry Applications, Vol. 36, No. 5, pp. 1369–1379, 2000.

[33] D. Hadiouche, H. Razik, And A. Rezzoug, “On The Design of Dual-Stator Windings for Safe Vsi Fed Ac Machine Drives,” Conference Record of the 2001 IEEE Industry Applications Conference. 36th IAS Annual Meeting (Cat. No.01CH37248), Chicago, IL, USA, 2001, pp. 1123-1130 vol.2,, doi: 10.1109/IAS.2001.955624

[34] M. Cheng and P. Han, "A Dual-Stator Brushless Doubly-Fed Induction Motor for EV / HEV Applications". 2014 International Conference on Intelligent Green Building and Smart Grid (IGBSG), Taipei, Taiwan, 2014, pp. 1-6, doi: 10.1109/IGBSG.2014.6835258.

[35] Z. Heidari, H. Gorginpour, And M. Shahparasti, "Optimal Electromagnetic-Thermal Design of a Seven-Phase Induction Motor for High-Power Speed-Control Applications", "international journal of science & technology, Vol. 29, Issue 5, pp. 2480–2497, 2022, Doi: 10.24200/Sci.2021.54766.4028.

[36] H. Chen, J. Zhao, H. Wang, Q. Zhang, X. Luo, And H. Xu, "Multi-Objective Optimum Design of Five-Phase Squirrel Cage Induction Motor by Differential Evolution Algorithm," Energy Reports, Vol. 8, Pp. 51–62, 2022, Doi: 10.1016/J.Egyr.2022.09.098.

[37] K. Pienkowski, "Analysis and Control of Dual Stator Winding Induction Motor," Archives of Electrical Engineering, Vol. 61, No. 3, pp. 421–438, 2012, Doi: 10.2478/V10171-012-0033-Z.

[38] I. Tamrakar, "power factor correction of induction motors using PWM inverter fed auxiliary stator winding," IEEE transactions on energy conversion, vol. 14, no. 3, pp. 426–432, 1999, , doi: 10.1109/60.790892

[39] S. Basak, S. Member, C. Chakraborty, And B. C. Pal, "A New Configuration of Dual Stator Induction Generator Employing Series and Shunt Capacitors," IEEE transactions on energy conversion, Vol. 8969, No. C, Pp. 1–10, 2017, doi:

[40] R. Bojoi, A. Tenconi, F. Reofumo, G. Griva, D. Martinello, "Complete Analysis And Comparative Study of digital modulation Techiques for Dual Three Phase AC motor Drives," 2002 IEEE 33rd Annual IEEE Power Electronics Specialists Conference. Proceedings (Cat. No.02CH37289), Cairns, QLD, Australia, 2002, pp. 851-857 vol.2, doi: 10.1109/PSEC.2002.1022560

[41] M. Jagiela, X. Wang, R. A. Mcmahon, And T. Garbiec, "Time-harmonic field-circuit model for brushless doubly fed induction machine," IET Electric Power Applications, original research,Vol.17, Issue 7, Pp. 965-975, 2023, Doi: doi.org/10.1049/elp2.12317

[42] A. R. Soman, S. Madaan, S. Gupta, A. Singh, And V. Yadav, "Performance Analysis of Dual Stator Induction Motor," International Research Journal of Engineering and Technology, Volume: 05 Issue: 05 Pp. 1969–1973, 2018.

[43] P. R. Burande, "Simulation of 3-Phase 2- Stator Induction Motor Using Matlab Platform," International Journal of Applied Engineering Research, Vol. 13, No. 11, Pp. 9437–9441, 2018.

[44] R. Sardar and P. A. R. Soman, "Multispeed Operation of Dual Stator Winding Induction Motor," IJSRSET, Vol. 2, No. 2, Pp. 994–999, 2016.

[45] A. R. Soman, "Variation in Torque of Dswim by Just Changing Voltage Keeping Speed Constant," Asian Journal of Convergence in Technology, Vol. V, No. I, Pp. 1–4, 2019.

[46] F. Bu, Y. Hu, W. Huang, And S. Zhuang, "Parameter Design and Static Performance of Dual Stator-Winding Induction Generator Variable Frequency Ac Generating System with Inductive and Capacitive Loads," IEEE transactions on industrial electronics, Vol. 61, No. 8, Pp. 3902–3914, 2014, doi: 10.1109/TIE.2013.2286571

[47] M. Haussmann, J. Weigold, W. Wondrak, M. Doppelbauer, D. Ag, And T. Hpc, "Characterization of Dual Stator Induction Machines," 32nd Electric Vehicle Symposium, Pp. 1–8, 2019.

[48] M. Haussmann, C. Kloeffer, J. Weigold, W. Wondrak, M. Doppelbauer, And D. Ag, "Parameter Identification of a Dual Stator Induction Machine," 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), Warsaw, Poland, 2017, pp. P.1-P.10, doi: 10.23919/EPE17ECCEEurope.2017.8099250

[49] R. Bojoi, F. Farina, G. Griva, F. Profumo, S. Member, And A. Tenconi, "Direct Torque Control for Dual Three-Phase Induction Motor Drives," IEEE transactions on industry applications, Vol. 41, No. 6, Pp. 1627–1636, 2005, doi: 10.1109/TIA.2005.858281

[50] A. Boglietti Et Al., "Efficiency Analysis of Pwm Inverter Fed Three-Phase and Dual Three-Phase Induction Machines," Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting, Tampa, FL, USA, 2006, pp. 434-440, doi: 10.1109/IAS.2006.256557

[51] A. Boglietti, S. Member, R. Bojoi, A. Cavagnino, And A. Tenconi, "Efficiency Analysis of Pwm Inverter Fed Three-Phase and Dual Three-Phase High Frequency Induction Machines for Low / Medium Power Applications," IEEE transactions on industrial electronics, Vol. 55, No. 5, Pp. 2015–2023, 2015, doi: 10.1109/IAS.2006.256557

[52] K. Houari, A. Massoum, And A. Meroufel, "Dual Star Induction Motor Drive: Modelling, Supplying and Control," International Journal of Electrical and Power Engineering, vol. 5, No. 1, 2011.

[53] D. Hadiouche, H. Razik, S. Member, And A. Rezzoug, "On The Modeling and Design of Dual-Stator Windings to Minimize Circulating Harmonic Currents for Vsi Fed Ac Machines," IEEE transactions on industry applications, Vol. 40, No. 2, Pp. 506–515, 2004, doi: 10.1109/TIA.2004.824511

[54] O. Rabiaa, B. H. Mouna, D. Mehdi, And S. Lassaad, "Modeling of A Dual-Three-Phase Induction Motor Including the Effect of Stator Mutual Leakage Inductance," 2017 International Conference on Green Energy Conversion Systems (GECS), Hammamet, Tunisia, 2017, pp. 1-5 2017, doi: 10.1109/GECS.2017.8066131

[55] G. Renukadevi and K. Rajambal, "Generalized D-Q Model of N-Phase Induction Motor," International Journal of Electrical and Computer Engineering, Vol. 6, No. 9, Pp. 1066–1075, 2012.

[56] J. M. Guerrero and O. Ojo, "Total Air-Gap Flux Minimization in Dual Stator Winding Induction Machines," 2008 Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition, Austin, TX, USA, 2008, pp. 1132-1138, doi: 10.1109/APEC.2008.4522864

[57] A. S. O. Ogunjuyigbe, T. R. Ayodele, And B. B. Adetokun, "Engineering Science And Technology, An International Journal Modelling And Analysis Of Dual Stator-Winding Induction Machine Using Complex

Vector Approach," Eng. Sci. Technol. An Int. J., Vol. 21, No. 3, pp. 351–363, 2018.

[58] Y. Zhao, T. A. Lipo, "Space Vector PWM Control of Dual Three-phase Induction Machine Using Vector Space Decomposition", IEEE transactions on industry applications, Vol. 31, No. 5, 1995, doi: 10.1109/28.464525

[59] R. Gregor, F. Barrero, S. L. Toral, And M. J. Duran, "Realization of an Asynchronous Six-Phase Induction Motor Drive Test-Rig Realization of an Asynchronous Six-Phase Induction Motor Drive Test-Rig," RE&PQJ, Vol. 1, No. 6, 2008.

[60] B. S. Marwa, "Modeling and Analysis of Double Stator Induction Machine Supplied by A Multi-Level Inverter," IEEE, No. 9, Pp. 269–272, 2012, doi: 10.1109/MELCON.2012.6196430

[61] Y. Bensalem and M. N. Abdelkrim, "Modeling and Simulation of Induction Motor Based On Finite Element Analysis," IJPEDS, Vol. 7, No. 4, Pp. 1100–1109, 2016.

[62] R. H. Nelson, P. C. Krause, "Induction Machine Analysis for Arbitrary Displacement Between Multiple Winding Sets", in IEEE Transactions on Power Apparatus and Systems, vol. PAS-93, no. 3, pp. 841-848, May 1974, doi: 10.1109/TPAS.1974.293983

[63] M. B. Fredj, M. B. Slimene, M. A. Khlifi, H. Rehaoulia, "Study of Association of Dual Stator Winding Induction Machine," IJESRT, Vol. 5, No. 4, Pp. 85–92, 2016.

[64] A. Rehaoulia, H. Rehaoulia, and F. Fnaiech "Double Star Induction Machine Modelling: Impact of The Stator Mutual Leakage Inductance", international journal of applied electromagnetics and machine, vol. 53, no. 1, pp. 51-61, 2017, doi: 10.3233/JAE-150160

[65] D. Nascimento, I. Automatyki, And L. Wan, "Electromagnetic Fields On 3-Phase Induction Motor Using Finite Element Analysis," 2021 IEEE International Joint EMC/SI/PI and EMC Europe Symposium, Raleigh, NC, USA, 2021, pp. 434-439, doi: 10.1109/EMC/SI/PI/EMCEurope52599.2021.9559357.

[66] B. S. Marwa and B. F. Mouldi, "Dual Stator Induction Motor Operation from Two Pwm Voltage Source Inverters" 2013 International Conference on Electrical Engineering and Software Applications, Hammamet, Tunisia, 2013, pp. 1-4, doi: 10.1109/ICEESA.2013.6578383

[67] L. Alberti, N. Bianchi, And S. Member, "Experimental Tests of Dual Three-Phase Induction Motor Under Faulty Operating Condition," IEEE Transactions on Industrial Electronics, Vol. 59, No. 5, Pp. 2041–2048, 2012, doi: 10.1109/TIE.2011.2171175

[68] Kaneo Takaku, "Computer Aided Analysis of a Twin Stator Induction Motor", Conference Record of the IEEE Industry Applications Society Annual Meeting,, San Diego, CA, USA, 1989, pp. 289-294 vol.1, doi: 10.1109/IAS.1989.96666

[69] E. Nakamae, H. Yamashita, K. Kaneda, Y. Ohnogi, K.Kagawa, "Noiseless Variable-Speed Siquirrel Cage Induction Motor", IEEE transactions on energy conersion, Vol. 5, No. 2, Pp. 380–385, 1990, doi: 10.1109/60.107236

[70] N. Chilakapati, "Investigation of Doubly Fed Twin Stator Induction Motor As A Variable Speed Drive," 1998 International Conference on Power Electronic Drives and Energy Systems for Industrial Growth, 1998. Proceedings., Perth, WA, Australia, 1998, pp. 160-165 Vol.1, doi: 10.1109/PEDES.1998.1330007.

[71] B. H. Band and A. D. Ingole, "Transfer of Power by Using Two Induction Machines," IJCESR Conference, No. 8, Pp. 36–40, 2017.

[72] A. Pugachev, And A. Kosmodamianskiy, "Two Induction Motors Electric Drive With Rotatory Stator," Journal of Electrical Engineering, vol. 16, no. 4, Pp. 54-60, 2016.

[73] L. Bu Et Al., "A New Energy Recovery Double Winding Cage-Rotor," IEEE transactions on energy conversion, Vol. 18, No. 2, Pp. 315–320, 2003, doi: 10.1109/TEC.2003.811736

[74] M. Sowmiya and S. H. Thilagar, "Design and Performance Analysis of a Dual Stator Multiphase Induction Motor Using Finite Element Method," Indian Academy of Sciences, Vol. 46, ID. 67, 2021. https://doi.org/10.1007/s12046-021-01603-6

تقييم الماكنة الحثية المتعددة الاطوار والمتعددة الملفات: مراجعة

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الملخص

ان الماكنة الحثية مزدوجة الجزء الثابت (DSIM) تعتبر من المحركات المبتكرة التي تستخدم بشكل متزايد في السنوات الأخيرة. تتمثل المزايا الرئيسية في القدرة على العمل بكثافة فيض مغناطيسي أعلى، وكفاءة تشغيل اعلى، وقدرة اخراج عالية، إضافة الى تحسن في عزم الدوران الميكانيكي. تقدم هذه المقالة دراسة حول الماكنة الحثية متعددة اللفائف (سواء كانت ملفات الجزء الثابت المزدوجة ثابتة او قابله للدوران أو كانت متعددة الأطوار)، فيما يتعلق بتحسين التصميم وطرق التحليل وتقنيات النمذجة والمحاكاة. يتطلب تصميم DSWIM تعديلًا لهيكل الملفات للجزء الساكن للماكنة التقليدية، على عكس نموذج الماكنة الحثية ذات الجزء الثابت التوأم المنفصل الذي يتميز بالصعوبة والتعقيد في التصنيع والتركيب، وارتفاع كلفته. تقنية تحليل العنصر المحدد، والتحكم الاتجاهي، وتحليل الدائرة المكافئة، هي تقنيات تستخدم لتحليل ومحاكاة DSWIM في ظروف تشغيل مختلفة وكذلك لتحسين تصميم الماكينة لتطبيقات محددة. تبلغ زاوية إزاحة الطور المثالية بين ملفي الجزء الثابت في الماكنه ذات الملفات المزدوجة 30 درجة وتعتمد على عدد من المتغيرات، بما في ذلك تصميم الماكينة وبيئة التشغيل والتطبيق الذي تستخدم فيه الماكنة.

الكلمات الداله:
لماكنة الحثية مزدوجة الجزء الثابت، توأم الجزء الثابت، ملفات القدرة والتحكم، تحليل العنصر المحدد، ماكنة متعددة الاطوار، مولد حثي ذو ملفات مزدوجة.