Control Strategy for 5∅ Dual-Stator Winding Induction Starter/Generator Scheme

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Abstract:

This study presents a systematic regulation approach for a starter/generator(S/G) technology depending upon a (FPDWIM). The FPDWIM features two sets of stator windings and a cage-type rotor. The first was a 5∅ control winding (CW), while second is a 5∅ power winding (PW). The FPDWIM acts as a motor when it is turned on. The control winding drives the engine by providing both active and reactive power. The control winding handles reactive power in the producing phase, whereas the power winding delivers active power. To complete the combination of the beginning and producing control, ICWFOC is designed to perform in both starting and generating modes. The control winding current and flux are controlled in beginning mode to produce a consistent starting torque, while the control winding and power winding Direct Current bus voltages were controlled for producing mode. As a result, these methods' operational concepts and topologies remain equivalent, making implementation and performance easier. Using the suggested control method, this network may complete the starting-generating process having more better transitioning operation.

I. INTRODUCTION:

Further electric planes, electric autos, and additional uses are fastest emerging electrical technologies. IS (integrated starter/generator) systems are extremely efficient. Their low weight and volume make them intriguing [1]-[3]. The ISG is a group of people that work together to consists of two essential functions: In the initialization phase (1) In the first, the motor boosts the combustion rpm of the engines; (2) in the second, it acts as a generator in generating mode, which is powered by the engine. It's a generator that produces electricity. There are several varieties of the Electric equipment, such as electrical machineries, will be employed for ISG schemes. synchronous machines with wound-rotor brushes Switched reluctance motors [12]-[14], induction machines (IMs) [15]-[19], PMSM [7]-[9], hybrid excitation synchronous motor [10], [11], permanent-magnet synchronous motors [10], [11], switched reluctance machines [12].

Because of its simple construction, cheap cost, and ease of maintenance, induction machines become a viable choice designed for ISG schemes [15]-[17]. However, the torque density and reliability of IM-based ISG systems are limited in the beginning phase. To address these issues, research on multiphase induction machines created ISG schemes aimed at enhanced greater torque density in addition faults tolerancing has expanded significantly. In [18], a SLEM induction starter/generator to aircrafts is refined, the regulation technique is proven together excess then postfault processes.

For a mini-hybrid power train, a 6Ø induction starter/generator was constructed as well as tested to achieve strong initial torque a varied constant-power speeds range. In the beginning mode, multiphase IMs have a lot of torque and are quite reliable, but they have certain issues in the producing state.

First, during speed and load changes, the output performance remain shard for regulating [21]; second, high- frequency harmonics created by the converter shifts are passed to the loads, resulting in poor power quality [22],[23].

Many methods have been presented in the literature to alleviate the aforementioned issues. An integrated hybrid AC/DC producing system based on an open-winding induction generator with two converters is shown in [24] in terms of system topology. To get the greatest output power, control solutions based on model-based predictive direct torque control are studied [25]. [26] investigates a voltage-oriented decoupling control technique for reducing voltage and current harmonics. A novel kind of DWIG through a stationary excitation controller (SEC) is presented to increase performance. DWIG offers 2 different groups of stat or windings. They do not have an electrical connection, separating the DWIG's reactive as well as active power, but they are electro magnetically connected.

The SEC's capacity is limited since it primarily delivers reactive power to the DWIG, and high-frequency harmonics caused through regulators could be reduced. Dual stator winding induction generator takes the attention of the scientific community due to its features and benefits. Topology, regulation methods optimum designs, modelling, and study of operation states are among the pertinent works.

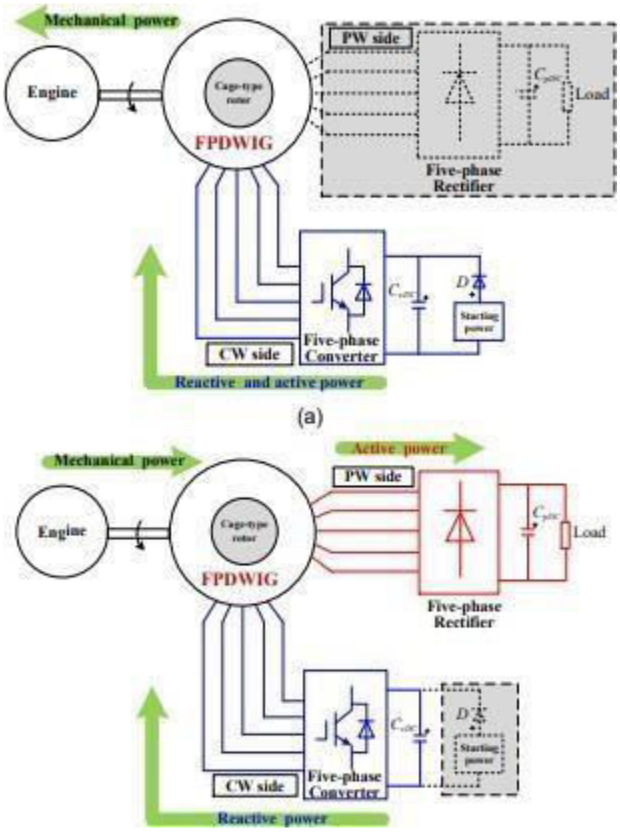
Recently, various novel topologies for the DWIG system have been developed. A novel DWIG arrangement utilizing series as well as shunt capacitor are described to improve voltage control and power quality. [38] investigates the Direct Current-bus-parallel architecture with a passive adjusted filer and its best current control method for extending the speed range in wind power applications. Other boost converter and Dual stator winding induction generator topologies are being researched [39]. Polyphase Dual stator winding induction generator combines the benefits with multiphase induction machines and DWIGs into one package. By third-harmonic injection, they may be used in DC producing systems with good performance and great power density, as demonstrated in [40]-[42]. Based on prior research, it is obvious that multiphase DWIG has a lot of promise in ISG systems. One of the most crucial factors to consider is the starter/generator control technique. There is, nevertheless, a research void on these topics. For5Ø dual-stat or winding induction machine-based starter/generator schemes, this work provides an integrated starter/generator control method based on ICWFOC. In the beginning mode, the control winding current is adjusted to manage the control winding flux and torque. it is controlled to manage the control winding and power winding dc voltages when in the producing mode. The purpose is to show that the physical quantities are smoothly regulated during the starting-generating operation modes, which comprise of four phases.

The following is a breakdown of the paper's structure. Section II contains a description of the 5Ø dual-stator winding induction machine starter/generator system. the suggested control method for the entire starting- generating process is introduced in Section III. In Section IV, the simulation results and analyses are presented. Section V includes the experimental data and related analyses in order to validate the proposed technique. Section VI draws some helpful findings.

II. 5Ø -STATOR WINDING IM-BASED STARTER/GENERATORSCHEME

A. System Topology

Figure 1 depicts the topologies of the 5Ø dual-stator winding induction machine -based starter/generator system in various modes of operation. the rotor of the 5Ø dual-stator winding induction machine is cage-style. on the stat or, there are two sets of windings. the first is known as five-phase control winding, and it is linked to the five-phase converter. the other is known as five-phase power winding, and it is connected to a diode rectifier to provide dc power. although the control winding and power winding have the same number of pole pairs and no electrical connections, they are electromagnetically connected. during the starting mode and to build-up the as shown in fig. 1(a) (starting mode), diode d switches on and the starting power supplies both active and reactive power for the 5Ø dual-stat or winding induction machine through the five-phase converter. the 5Ø dual-stator winding induction machine is a motor that produces torque to drive the engine. the power winding is turned off in this mode, and the 5Ø dual- stat or winding induction machine converts electric power to mechanical power. in most cases, the converter's capacity in the beginning mode is smaller than the generating capacity. the control winding and power winding dc bus voltages are initially built up in the generating mode. when the control winding dc bus voltage is larger than the starting power, diode d shuts off, as shown in fig. 1(b). the reactive power for the 5Ø dual-stator winding induction machine is mostly provided by the five-phase converter. the system enters table producing mode when the power windingd c bus voltage reaches its desired value. through a five-phase rectifier, the power winding delivers active power to dc loads. the 5Ø dual-stat or winding induction machine converts mechanical energy into electrical energy in this mode. there are three major advantages to this topology: (1) it has superior reliability because of its fault-tolerant capabilities when compared to three-phase induction machine -based s/g systems; (2) when compared to single-winding induction machine, the effect of converter-induced high-frequency harmonics on the loads may be limited or considerably reduced. this is due to the fact that the 5Ø dual-stator winding induction machine 's control winding and power
winding have electrical separation and the loads are not directly linked to the converter;
(3) the converter utilized in both beginning and generating modes is the same. furthermore, because the converter primarily deals with reactive power, its capacity is relatively low in the producing mode, allowing the hardware to be more compact for integration with the s/g system.



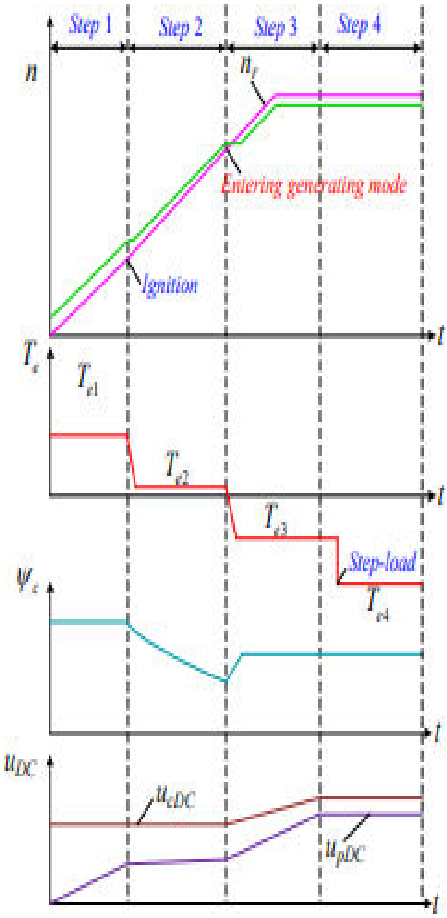


Fig. 1. The topologies of the 5∅ DUAL-STATOR WINDING INDUCTION MACHINE -based starter/generator system. (a) Starting mode. (b) Generating mode.

Fig. 2. The operating curves for different variables during the starting-generating process.

B. Principle and analysis of the starting-generation procedure

For various factors, the starting-generation procedure may be broken down into four parts, as illustrated in Fig. 2. The torque-speed characteristics of the system are shown in Figure 3.

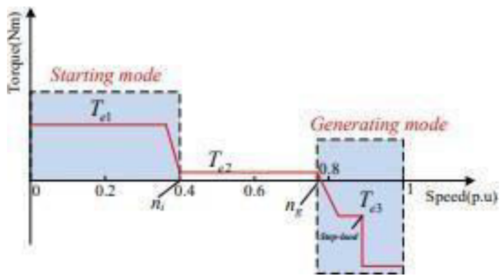


Fig. 3. The torque-speed characteristics of the 5∅ Dual-Stator Winding Induction Machine based S/G system

Step 1: The 5∅ dual-stator winding induction machine functions as a motor in the beginning mode. The control winding flux is continuous, and 5∅ dual-stat or winding induction machine drives the engine with a positive electromagnetic torque (Te1). The stator mmf speed (N_c) is higher than the rotor speed as the rotor accelerates (N_r).

Step 2: The engine accelerates and drives the 5∅ dual-stator winding induction machine when it reaches the ignition speed (N_i). The 5∅ dual-stat or winding induction machine begins the process of transitioning from the beginning to the generating modes. For overcoming the no-load torque, just a tiny positive electromagnetic torque (Te_2) is required. The control winding flux decreases as the rotor accelerates.

Step3: The rotor speed exceeds the stat or mmf speed when it reaches the generating speed (N_g). The electromagnetic torque goes after being +ve to being -ve (Te_3). The 5∅ dual-stator winding induction machine switches to voltage-built-up method, and the control winding flux progressively rises. The control winding and power winding Direct Current bus voltages have also been raised.

Step 4: The 5∅ dual-stator winding induction machine enters a steady generating method also delivers a continuous -ve electromagnetic torque when the control winding side and power winding Direct Current bus voltages range its command levels (Te_4).

III. REGULATION METHOD

Because the converter primarily provides reactive power for the 5∅ dual-stator winding induction machine in the producing mode, the ICWFOC method offers the advantages of ease of installation and a simple flux observer. As a result, it is appropriate for controlling the control winding and power winding dc bus voltages. The control techniques in both the beginning and generating modes of the ISG system are anticipated to be compatible for integration and high performance. The concepts and structures of the control methods in the starting and generating modes, as well as the generating mode, should be consistent in order to achieve this goal. The ICWFOC is also employed in the beginning mode because of this reason. This work proposes and describes an indirect control-winding-flux-oriented control -based integrated starter/generator controller approach.

A. The concept of integrating the starting as well as generating controls

Step1: When 5∅ dual-stat or winding induction machine is turned on, it acts like a motor. To operate the engine, the control winding flux must be constant in order to give adequate positive electromagnetic torque (Te_1). The stator mmf speed (N_c) is high compared to the rotor speed as the rotor accelerates (N_r). The 5∅ dual- stator winding induction machine's voltage equations and flow equations are as follows:

$$\begin{cases} u_{cd} = R_c i_{cd} + p\psi_{cd} - \omega_c \psi_{cq} \\ u_{cq} = R_c i_{cq} + p\psi_{cq} + \omega_c \psi_{cd} \\ 0 = R_r i_{rd} - \omega_s \psi_{rq} + p\psi_{rd} \\ 0 = R_r i_{rq} + \omega_s \psi_{rd} + p\psi_{rq} \end{cases} \qquad (1)$$

$$\begin{cases} \psi_{cd} = L_c i_{cd} + L_m (i_{rd} + i_{pd}) \\ \psi_{cq} = L_c i_{cq} + L_m (i_{rq} + i_{pq}) \\ \psi_{rd} = L_r i_{rd} + L_m (i_{cd} + i_{pd}) \\ \psi_{rq} = L_r i_{rq} + L_m (i_{cq} + i_{pq}) \end{cases} \quad (2)$$

The control winding flux orientation is employed in ICWFOC, and the control winding flux phasor is static on the d axis. As a result, C_d = c and C_q = 0. The five-phase converter linked to the control winding provides both active and reactive power in the beginning mode. Power Winding current components (I_{pd}, I_{pq}) are zero (Ipd = 0, Ipq = 0), thus the power winding rarely outputs electric power. As a result, (1) and (2) may be rephrased as

$$\begin{cases} u_{cd} = R_c i_{cd} + p\psi_{cd} \\ u_{cq} = R_c i_{cq} + \omega_c \psi_{cd} \\ 0 = R_r i_{rd} - \omega_s \psi_{rq} + p\psi_{rd} \\ 0 = R_r i_{rq} + \omega_s \psi_{rd} + p\psi_{rq} \end{cases} \quad (3)$$

$$\begin{cases} \psi_{cd} = L_c i_{cd} + L_m i_{rd} \\ 0 = L_c i_{cq} + L_m i_{rq} \\ \psi_{rd} = L_r i_{rd} + L_m i_{cd} \\ \psi_{rq} = L_r i_{rq} + L_m i_{cq} \end{cases} \quad (4)$$

$$i_{rq} + i_{pq} = -\frac{L_c}{L_m} i_{cq} \quad (5)$$

$$i_{rq} = -\frac{L_c}{L_m} i_{cq} \quad (6)$$

$$\psi_{rq} = -\frac{L_c L_r - L_m^2}{L_m} i_{cq} \quad (7)$$

$$\psi_{rd} = \frac{1}{\omega_s}(R_r \frac{L_c}{L_m} + p\frac{L_c L_r - L_m^2}{L_m}) i_{cq} \quad (8)$$

The approximate relationship between I_{rq} and I_{cq} can be expressed as: The

electromagnetic torque T_e can be written as follow:

$$\psi_c = \frac{1+\sigma T_r p}{1+T_r p} L_c i_{cd} - \frac{\omega_s T_r \sigma}{1+T_r p} L_c i_{cq} \quad (9)$$

$$T_e = \frac{5}{2} n_p \psi_{cd} i_{cq} = \frac{5}{2} n_p \frac{1+\sigma T_r p}{1+T_r p} L_c i_{cd} i_{cq} \quad (10)$$

$$\psi_c = L_c (i_{cd} - \omega_s T_r \sigma i_{cq}) \quad (11)$$

Infact, in the 5Ø dual-statorwindinginductionmachine, T_{ri} almost non-existent. As a result, the control winding flux is mostly affected by I_{cd}. To make the 5Ø dual-stator

$$\begin{cases} i_{cd1}^* = \dfrac{\psi_c^*}{L_c} \\ i_{cq1}^* = \dfrac{2T_{e1}}{5n_p\psi_c^*} \end{cases} \quad (12)$$

winding induction machine generate a beginning torque, regulate I_{cq} as a constant positive number starting from (10). As a result, the I_{cd} and I_{cq} command values in step 1 are as follows:

Step 2: As soon as the engine starts, it accelerates and drives the 5Ø dual-stator winding induction machine. The 5Ø dual-stator winding induction machine switches from the beginning to the producing mode. To overcome no-load torque in this technique, just a tiny positive electromagnetic torque (Te2) is required. As a result, T_e should be reduced from Te1 to Te2, and the control winding flux should gradually decrease as the rotor speed increases. The control winding angular frequency at the moment as soon as the engine ignition is defined as ci, and the commands value of I_{cd} in step 2 are as follows:

$$i_{cd2}^* = \frac{\omega_{ci}}{\omega_c}\frac{\psi_c^*}{L_c} = \frac{\omega_{ci}}{\omega_c} i_{cd1}^* \quad (13)$$

The control winding angular frequency c grows when the 5Ø dual-stator winding induction machine and engine speed up simultaneously. From (13) onwards, the I_{cd} falls

$$i_{cq2}^* = \frac{\omega_c}{\omega_{ci}}\frac{T_{e2}}{T_{e1}} i_{cq1}^* \quad (14)$$

$$\begin{cases} i_{cq2}^* = \dfrac{2T_{e1}}{5n_p\psi_c^*} - kt, & i_{cq2}^* \geq \dfrac{2T_{e2}}{5n_p\psi_c^*} \\ i_{cq2}^* = \dfrac{2T_{e2}}{5n_p\psi_c^*}, & i_{cq2}^* \leq \dfrac{2T_{e2}}{5n_p\psi_c^*} \end{cases} \quad (15)$$

progressively, as does the control winding flux. T_e decline from Te_1 to Te_2 must be controlled, according to

Step 3: The 5Ø dual-stator winding induction machine enters the generation mode as soon as the rotor speed ranges the generation speed. The electromagnetic torque shifts from +ve to -ve (Te3), and rotor speed progressively climbs beyond the stator mmf speed. The primary value of the command values of I_{cd} as well as I_{cq} whenever 5Ø dual-stator winding induction machine reaches Step 3 are as follows: (13) and (14).

$$\begin{cases} i_{cd3-initial}^* = \dfrac{\omega_{ci}}{\omega_{cg}} i_{cd1}^* \\ i_{cq3-initial}^* = \dfrac{\omega_{cg}}{\omega_{ci}}\dfrac{2T_{e2}}{5n_p\psi_c^*} i_{cq1}^* \end{cases} \quad (16)$$

$$\begin{cases} i^*_{cd3-initial} = \frac{\omega_{ci}}{\omega_{cg}} i^*_{cd1} + \mathbf{PI}_{pDC}(u^*_{pDC} - u_{pDC}) \\ i^*_{cq3-initial} = \frac{\omega_{cg}}{\omega_{ci}} \frac{2T_{e2}}{5n_p\psi^*_c} i^*_{cq1} - \mathbf{PI}_{cDC}(u^*_{cDC} - u_{cDC}) \end{cases} \quad (17)$$

Step 4: The 5Ø dual-stator winding induction machine arrives the constant generation method and outputs a continuous -ve electromagnetic torque when both the control winding and power winding dc bus voltages meet their command levels (Te4).

B. Operation of the projected integrated starter/generator regulation approach

Fig 4 depicts the recommended control method designed for the total starting-generating procedure. In Figure 4, switches S1 and S2 were used to choose the I_{cd} and I_{cq} command value in distinct stages, and they both shift at a time. Switch S1 and S2 contacts 1 in Step 1; switch S1 and S2 contacts 2 in Step 2. S1 and S2 connections are used in Steps 3 and 4. The summation of the final value in Step 2 and the output value of the 2 Proportional Integral regulators yields its command values of I_{cd} and I_{cq}. T_e (pc) and c (qc) can be regulated by I_{cq} and I_{cd}, respectively, in the beginning mode. I_{cq} and I_{cd} may control ucDC (pc) and upDC (qc) in the generating mode, respectively. The CONTROL WINDING active power (pc) and reactive power (qc) are always regulated by I_{cq} and I_{cd}, whether in beginning or producing mode. The control structures are constant in different phases as a result of this control between the two modes. Many considerations, such as dynamic performance and system stability, should be considered while designing the parameters for the four PI controllers. The settings of four PI controllers are eventually developed using a mix of simulated research and practice. In the Appendix, the limitations of the Proportional Integral regulators are utilized.

IV. SIMULATION RESULTS

A simulation model is developed in the MATLAB/Simulink environment to verify the viability of the suggested control technique. The prototype's parameters are presented in Appendix. When the 5 Ø dual- stat or winding induction machine is in the beginning mode, the engine's ignition speed is set to 600 rpm to recreate the whole starting-generating process. The engine accelerates as soon as it is started the 5Ø dual-stator winding induction machine starts generating mode when the rotor speed reaches 1300rpm. The 5Ø dual-stator winding induction machine operates in stable producing mode after the starting-generating procedure, with a rated step-load integrated. Figure 5 depicts the simulated results for the entire starting- generating procedure.

The 5Ø dual-stator winding induction machine generates a continuous positive electromagnetic torque in Step 1. The control winding q-axis current is kept at around 5 amps. The active and reactive power of control winding both grow. The control winding Direct current bus voltage is around 270V, it is calculated by taking the voltage percentage of the mutual starting power also the control winding phase voltage into account.

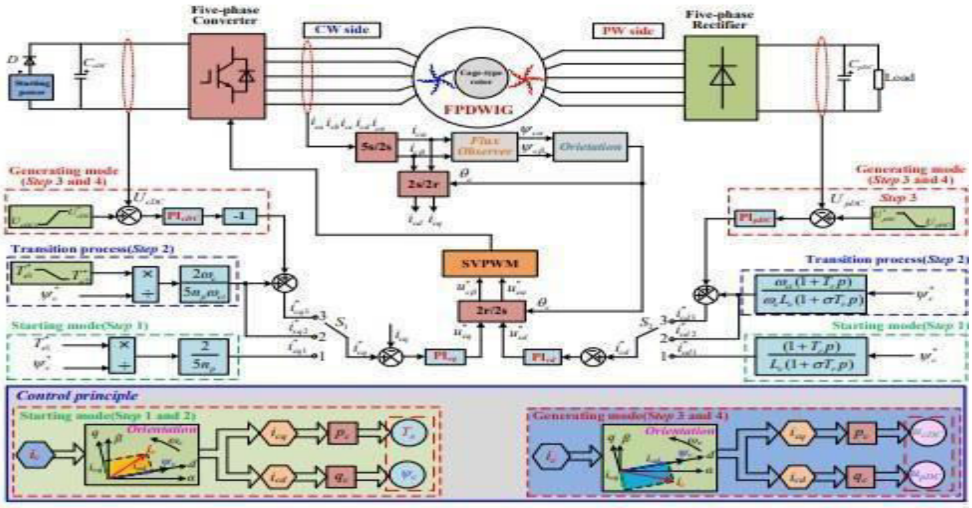
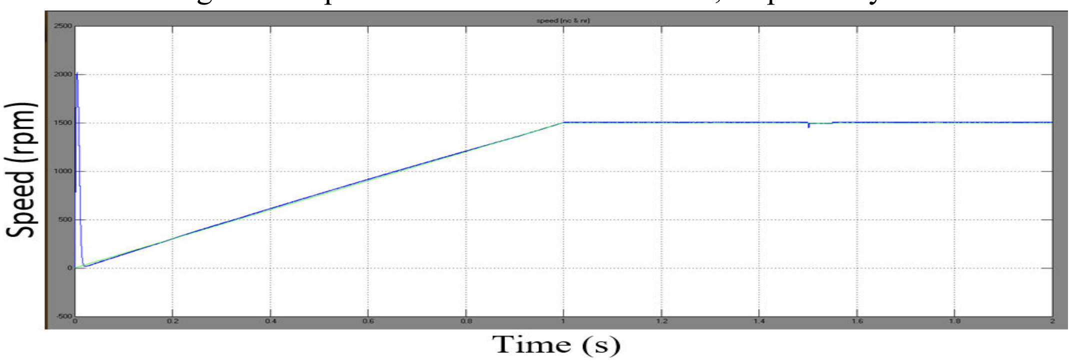


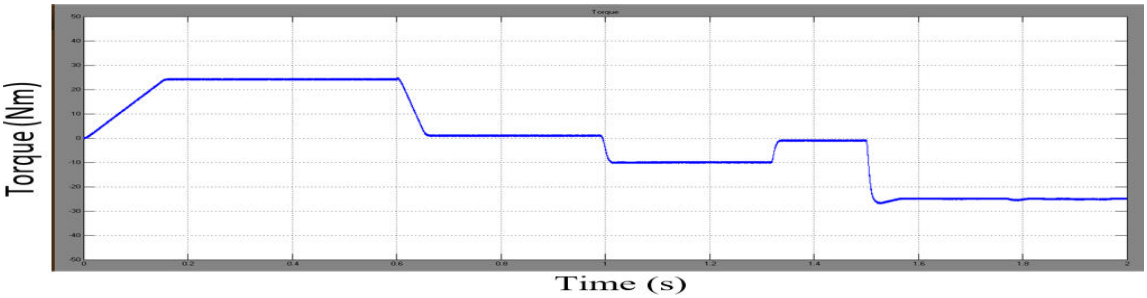
Fig. 4. Block for regulation approach of entire starting-generation procedure.

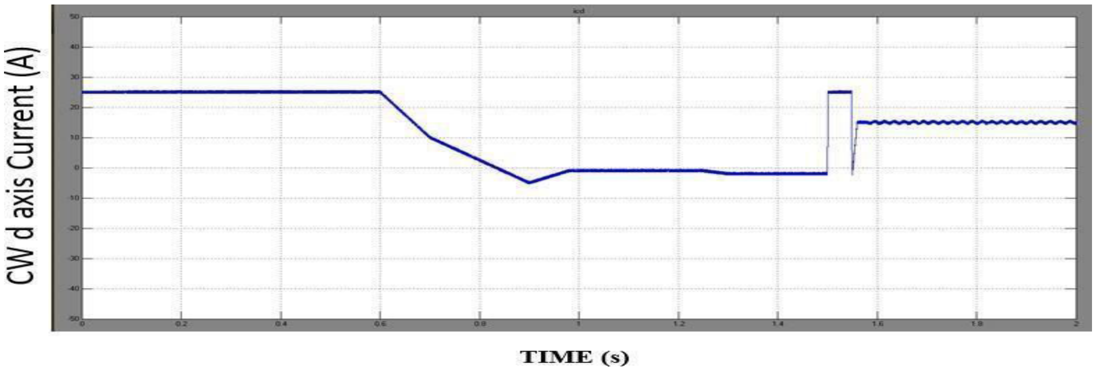
The 5∅ dual-stator winding induction machine only delivers a little amount of positive electromagnetic torque in Step 2 to eliminate the no-load torque. The current in control winding q-axis reduces from around 4A to about 1A. As a result, the control winding active power is relatively low. The reactive power steadily decreases as the rotor speed increases. The control winding does not produce any electric power when it is in the beginning mode.

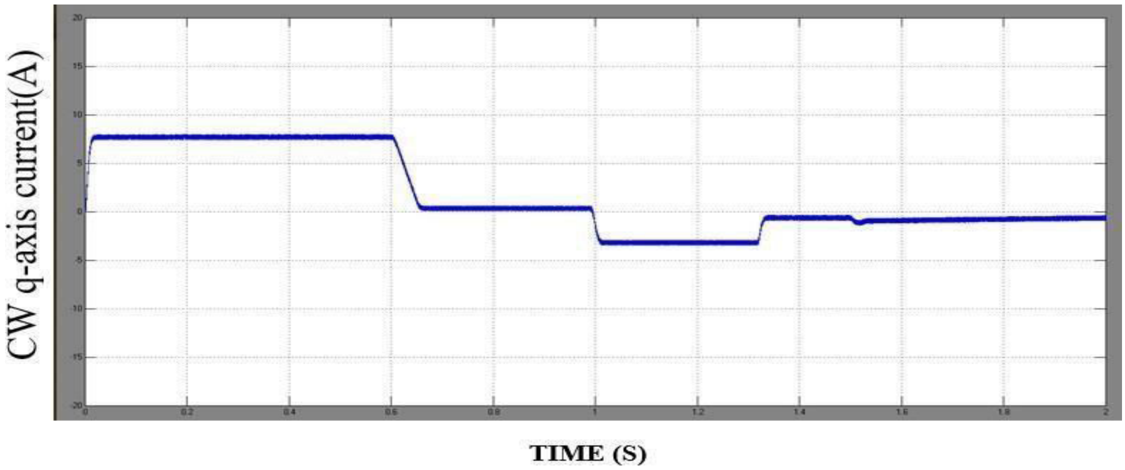
In Step 3, the 5∅ dual-stat or winding induction machine's electromagnetic torque gradually declines from a +ve to a -ve values, and rotor speed exceeds the stator mmf speed. The control winding as well as power winding Direct Current bus voltages both reach their command levels (about 350V and 270V, respectively). The voltage rate of the diode rectifier is used to determine the value of the power winding dc bus voltage. While the control winding Direct Current bus voltage value is chosen to ensure that the control winding Direct Current bus can operate in dependently in the producing mode. Because the control winding requires output active power to sustain the control winding direct current bus voltage, the q-axis current and active power are negative. For the power winding direct current bus voltage build- up, the control winding reactive power is controlled.

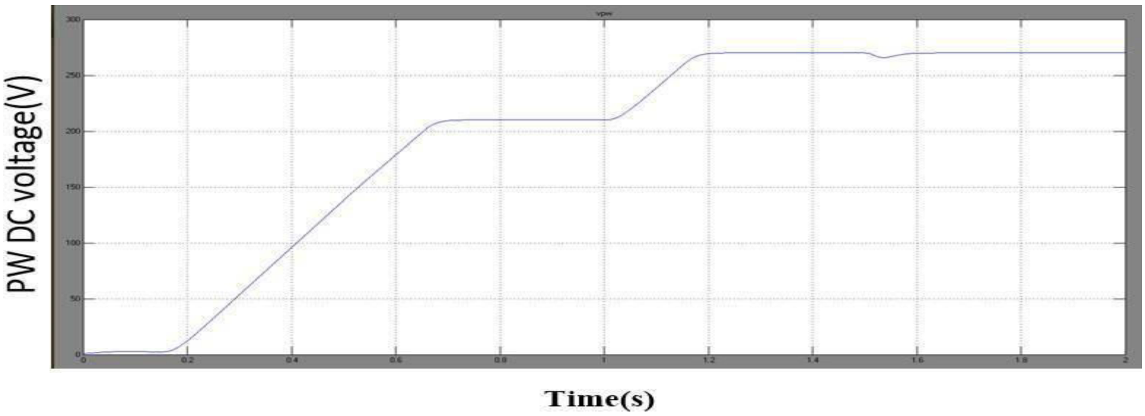
the 5∅ dual-stator winding induction machine enters a stable generating state in Step 4. The rotor speed remains constant at the specified value (1500 rpm). The control winding and power winding direct current bus voltages are kept at around 350 and 270 volts, respectively.

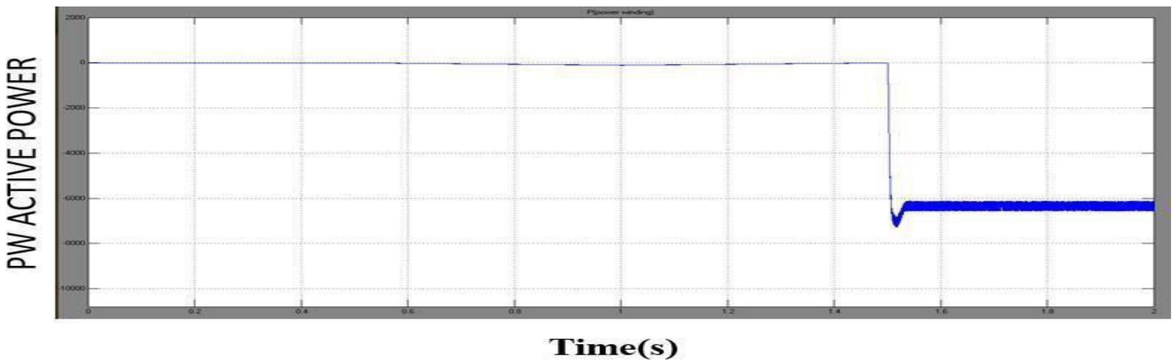



Torque (Nm)
Time (s)


CW d axis Current (A)
TIME (s)


CW q-axis current(A)
TIME (S)


PW DC voltage(V)
Time(s)



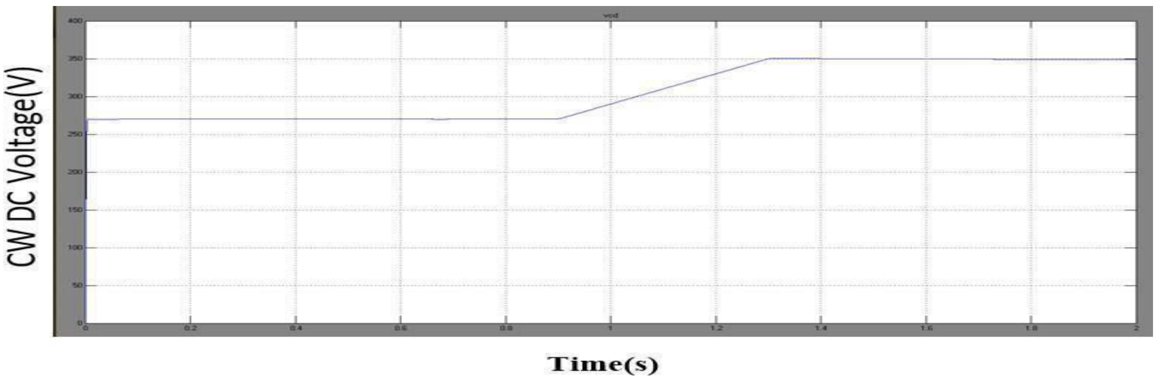


Fig. 5. The simulation results (a) Rotor and stator speed. (b) Torque (Nm). (c) The CONTROL WINDING d-axis current. (d) The CONTROL WINDING d-axis current. (e) The POWER WINDING Direct Current

bus voltage. (f) The control winding direct current bus voltage. (g) the control winding active and reactive power. (h) the power winding active power.

the 5∅ dual-stat or winding induction machine can run continuously throughout the whole starting-generating procedure. all of the variables do not change abruptly, indicating that the system can seamlessly transition from the beginning to the producing modes.

the control winding flux and d-axis current rise by the step-load of esteemed power in the constant producing method, allowing the power winding direct current bus voltage to return to the reference values. these power winding generates around 5kw active power and the control winding reactive power is enhanced. The simulation results demonstrate that the suggested control approach can successfully govern the entire starting- generating process while maintaining high compatibility and performance across various phases.

VI. CONCLUSION

this study proposes a control technique for a 5∅ dual-stat or winding induction machine-based s/g system. ICWFOC is used in both the beginning and generating modes to achieve the integration of the starting as well as generation control. the control winding provides both active and reactive power through a five-phase converter in the beginning mode. to provide a constant flux and sufficient beginning torque, the control winding d-axis and q-axis currents are kept constant. the control winding primarily supplies reactive power in the producing mode, whereas the power winding produces direct current electric power over the rectifier. both the control winding and power winding direct current bus voltages are regulated by two voltage- loops, and the control winding direct-axis and quadrature-axis currents were controlled by the control winding and power winding direct current bus voltages. the integrated starter/generator control is achieved using consistent structures and concepts for regulation techniques, as well as for diverse modes. the execution is straightforward and effective. the simulation and experimental findings support the suggested control strategy's validity. the system can function continuously during the whole starting-producing process, and both dynamic and static performance in the generating mode have been obtained with good results in the generating mode. many features of the s/g system, such as improving the power density, sensor less control, fault-tolerant control

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