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Comparative Analysis of Direct and Soft Starting Method for Induction Motor on Difference Load Levels

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Asynchronous machines are considered nowadays the most commonly used electrical machines, which are mainly used as electrical induction motors. The induction motors, which is considered as the backbone of industrial applications and operation, demand a reliable and efficient starting method to minimize mechanical stress and electrical disturbances. This research study presents a comparative analysis of Direct Online (DOL) and Soft Starter techniques for three-phase induction motors, utilizing MATLAB/Simulink software for simulation and performance evaluation. The simulation results highlight the effectiveness of the soft starter in achieving a faster and more controlled start-up, making it a superior choice in applications where reducing start-up transients and mechanical wear is critical such as conveyors, pumps and compressors. This was achieved by deploying a 35-kW induction motor to analyze the performance of direct online (DOL) starters and

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soft starters, with a particular focus on the latter's use of a thyristor block to mitigate inrush current. The analysis was carried out at different load conditions, such as no load, 25% load, 50% load, 75% load, and 100% load. The result obtained shows that, the direct online takes longer transient than the soft starter, for example, during no load test direct online transient time was 0.4 second while soft starter was 0.2 second. This study underscores the significance of advanced simulation tools in optimizing motor startup strategies, thereby enhancing the efficiency and longevity of three-phase induction motors.

Keywords: Induction motors; soft starter; direct online starter; rotor speed; electromagnetic torque and stator current.

1. INTRODUCTION

Asynchronous machines are considered nowadays the most commonly used electrical machines, which are mainly used as electrical induction motors. The induction motors, which is considered as the backbone of industrial applications and operation, demand a reliable and efficient starting method to minimize mechanical stress and electrical disturbances [1,2,3]. Starting of a three-phase induction motor has a significant transient effect on the power system stability due to high starting current [4] [5,6]. The value of transient parameters, and its during can impair negatively on a given system if not properly managed. The starting transient parameters must satisfy the transient characteristics requirements with minimized starting current and settling time suitable for operation within some electrical and electronics system with sensitive that components that cant withstand sudden current rise. If the starting technique is suitable, the life of the induction would be prolonged, and this can lead to some economic benefits.

Gonzalez, Zenginobuz, Hammid, Umoette, Umoette, Umoette, Reddy, Okpo [7-14]. Some works have been done in the induction motor starting techniques, aiming at improving the transient parameter values.

According to [7], who proposed a saturation and a deep bar effect for the study of transients of three-phase squirrel-cage type induction motors. The researchers use mathematical model of an induction motor to expressed the six differential equations of three-phase instantaneous voltage and current. Similarly, [8] presents a quality mathematical model of induction machine based on the steady state and dynamic equations and D-Q transformation technique. The model was used for steady state as well as transient analysis of squirrel cage or wound rotor structure. Simulation of three phase induction motor in MATLAB with Direct and Soft starting methods was carried out in [9], The theory behind the research was based on representing the real motor by a set of equations and values in MATLAB using the subsystem feature, forming a corresponding idealistic motor in a way where all the physical effects are similar. The motor was started under different loads in two methods: Direct and Soft starting. Each method was studied and discussed using supporting simulation of currents, torque, speed, efficiency and power factor curves. Linear and nonlinear controllers can also be used to control the starting operation of an induction motor driving a system which can include system powered by renewable energies [11,15,4,5].

For example, [12] developed a model of induction motor drive for speed control using a hybrid controller consisting of proportional integral derivative (PID) and fuzzy logic, and the target load was a nonlinear load like a pump. The model gave an improved response when compared to either fuzzy logic or PID controller. In [16], dynamic response using a fuzzy logic controller (FLC) was compared with a proportional integral (PI) controller; the latter showed superior performance at from the current and Electromagnetic torque response In [17], particle swarm optimization (PSO) was used in getting an optimized value of starting current, while [18] proposed a novel hybrid control of IM based on the combination of direct torque control (DTC) and genetic algorithm. The control method showed good performance at only one operating speed. A novel research algorithm was proposed in [15] and [6] to improve the design of the FLC and FLC-PIC, respectively, for IM starting current and electromagnetic torque. The proposed algorithm provides an easy approach for obtaining membership functions. The developed controller provided the needed stability and good dynamic response under speed and mechanical load change [6]. Developed an optimized hybrid controller model for vector speed control technique on variable speed and intermittent loading operating conditions. The speed range considered was lower in the region of 5 to 30 rad/sec. The study was useful in the Lower speed applications [19]. Studied the different methodologies of IM drives control. The study showed that speed, power, and efficiency of IM have been controlled by various techniques like frequency control, supply voltage control, and the multiple stator winding method. Implementation of IFOC on IM drive with PI control was presented in [11], and the results show a good dynamic response on intermittent loading operating conditions [10]. Used a finite element analysis approach to obtain the dynamic performance of IM under intermittent loading conditions without control.

The simulation results of the cited literature show that sensitive parameters like starting current and settling time of the transients response still need a research attention modern industrial applications like cranes, and robotics.

2. METHODOLOGY

From the flow chart, literature reviewed on three-phase induction motor transient effects on direct online starter and soft starter was first carried out, this follows by developing and mathematical expression to size the three-phase induction motor parameter, and the torque equation was used as shown in Fig. 1. After sizing the induction motor, a review was carried out again to choose a situation software for modelling and simulating of the system. MATLAB/Simulink simulation soft was chosen because it provides a comprehensive environment for modeling, simulating, and analyzing complex systems. It's also allowed for detailed modeling of the behavior of induction motors under different operating conditions as well as integrating seamlessly with other MATLAB toolboxes and software packages, enabling engineers to perform multidomain simulations and incorporate additional functionalities such as signal processing, control system design, and optimization. The system for both direct on-line and soft starter was modeled with appropriate functional block in Simulink library

The modeled was simulated and their output waveform was studied and improve upon where it is necessary. The Simulink model of direct on line starter and soft starter are shown in Figs. 2 and 3 respectively.

3. ANALYTICAL MODELLING OF SCIM

SCIM is an AC machine whose speed at loading conditions is always less than the synchronous speed, and it operates on the principle of electromagnetic induction [7] and [20] analyzed the performance of SCIM in steady-state conditions [21,22]. Also outlined the design strategy for achieving a desired performance.

The voltage equations of SCIM in dq0 axis using analytical method are given equation (1) – (4):

$$v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega_e \varphi_{ds} \quad (1)$$

$$v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_e \varphi_{qs} \quad (2)$$

$$v_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega_e - \omega_r)\varphi_{dr} \quad (3)$$

$$v_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_e - \omega_r)\varphi_{qr} \quad (4)$$

and

$$v_{qr} = v_{dr} = 0$$

The flux equation:

$$\varphi_{qs} = L_{Is} i_{qs} + L_m(i_{qs} + i_{qr}) \quad (5)$$

$$\varphi_{qr} = L_{Ir} i_{qr} + L_m(i_{qs} + i_{qr}) \quad (6)$$

$$\varphi_{ds} = L_{Is} i_{ds} + L_m(i_{ds} + i_{dr}) \quad (7)$$

$$\varphi_{dr} = L_{Ir} i_{dr} + L_m(i_{ds} + i_{dr}) \quad (8)$$

where v_{qs} , v_{ds} are the applied voltages to the stator, i_{ds}, i_{qs}, i_{dr} , i_{qr} are the corresponding d and q axis stator current and rotor currents. $\varphi_{qs,}\varphi_{qr}$, φ_{ds}, φ_{dr} , are the rotor flux component, R_s , R_r are the stator and rotor resistances, L_{Is}, L_{Ir} denotes stator and rotor inductances, whereas L_m is the mutual inductance [23,24,25-30]. Combining the flux equation with (1), (2), (3) and (4), the electrical transient model in term of voltage and current can be represents in matrix form as:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + SL_S & \omega_e L_S & SL_m & \omega_e L_m \\ -\omega_e L_S & R_s + SL_S & -\omega_e L_m & SL_m \\ SL_m & (\omega_e - \omega_r)L_m & R_s + SL_S & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & SL_m & -(\omega_e - \omega_r)L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (9)$$

where, S is the Laplace operator. (9):

The electromagnetic torque equation given in equation (10):

$$T_e = \frac{3PL_m}{4L_r}(\varphi_{dr}i_{qs} - \varphi_{qr}i_{ds}) \quad (10)$$

where *P*, denote the pole number of the motor. If the vector control is fulfilled, the q component of the rotor field φ_{qr} would be zero. Then the electromagnetic torque is controlled only by q-axis stator current and is shown in equation (11):

$$T_e = \frac{3PL_m}{4L_r}(\varphi_{dr}i_{qs}) \quad (11)$$

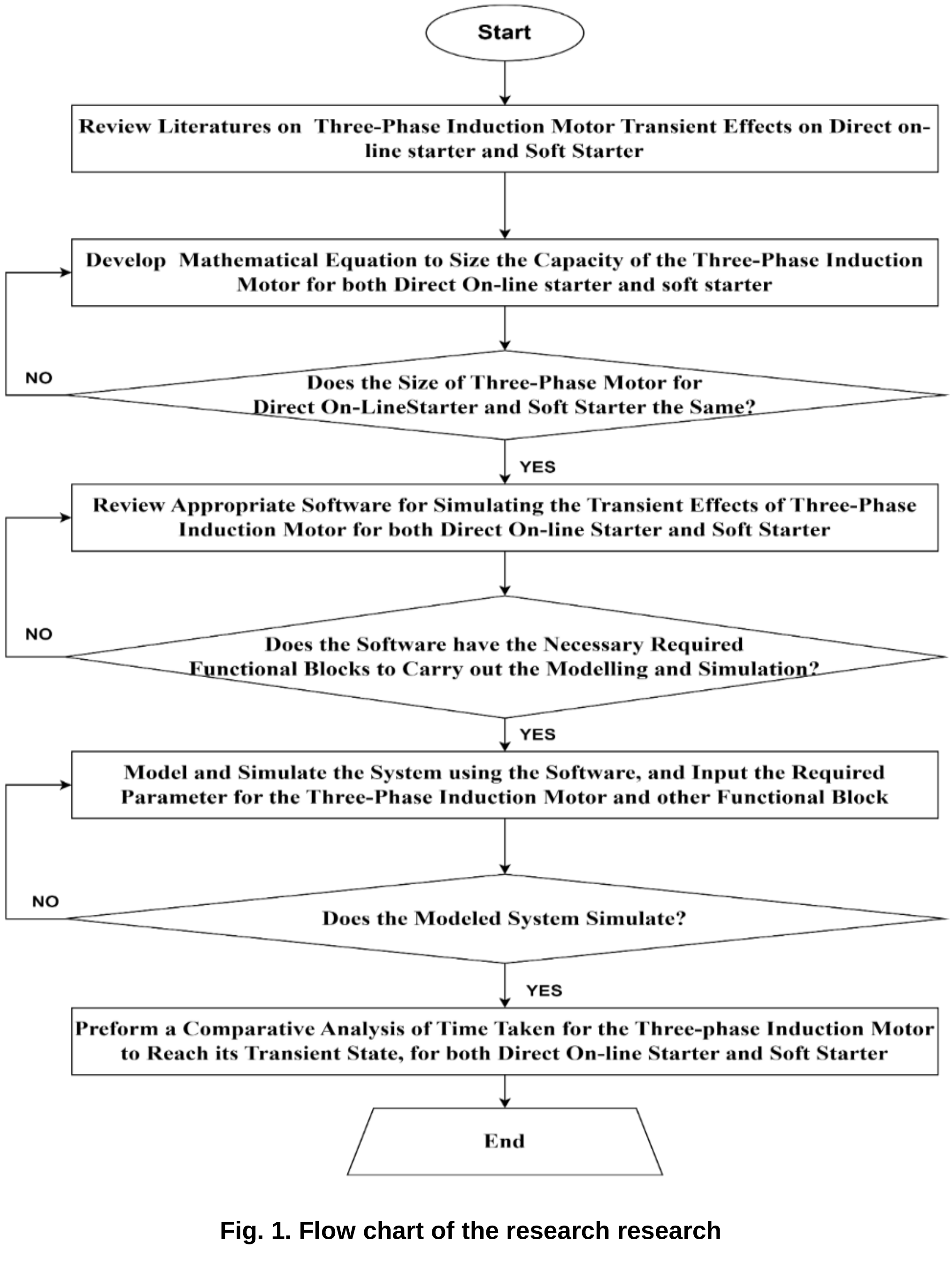


Fig. 1. Flow chart of the research research

Table 1. Specification of the Asynchronous Machine Rated Parameters

Number	Parameters	Value
1	Input power of the motor	37Kw
2	Motor input voltage	400V
3	Frequency	50Hz
4	Motor speed	1480 RPM
5	Mechanical input	$238.7\ N*m$
6	Mechanical power	37Kw
7	Stator resistance	0.08233Ω
8	Stator inductance	0.000724 mH
9	Rotor resistance	0.05037Ω
10	Rotor inductance	0.000724 mH
11	Mutual inductance	0.02711H
12	Inertia(J)	0.37 (kg.m^2)
13	Friction factor(F)	0.02791 (N.m.s)
14	Number of pole pair	4
15	Initial condition	10000000

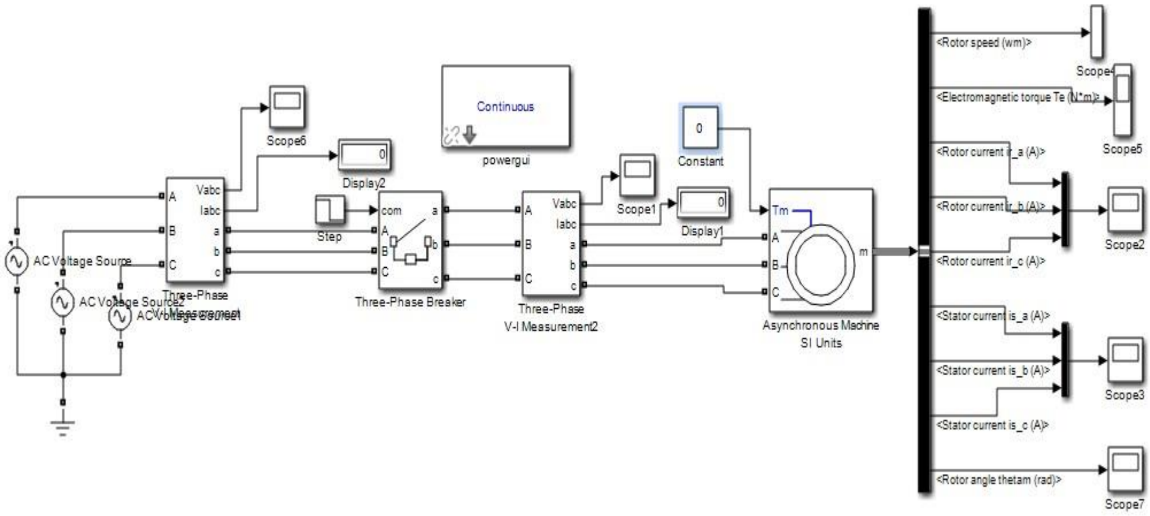


Fig. 2. SIMULINK model of direct online starter

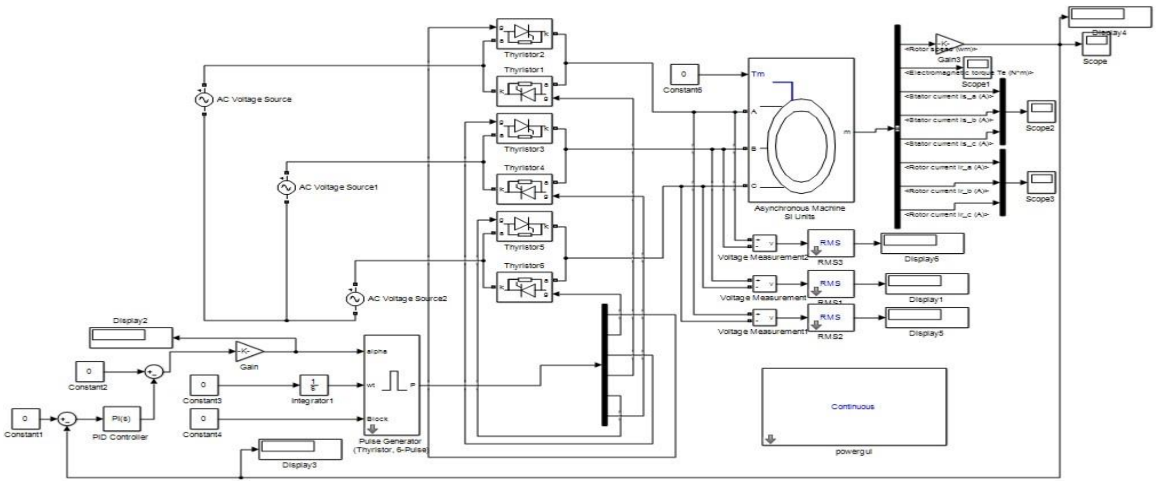


Fig. 3. SIMULINK model soft starter

The modeled was simulated and their output waveform was studied and improve upon where it is necessary. The Simulink model of direct on line starter and soft starter are shown in Figs. 2 and 3 respectively.

4. RESULTS AND DISCUSSION

The starting performance of an induction motor with direct online and soft starter at different loading conditions is presented in this section. The parameters of the tested motor are listed in Table 1. The design and simulation were carried out using the Simulink toolbox of MATLAB. The starters were separately designed for induction starting technique at different levels of load. The speed, torque, and current responses of induction motors with these starters were studied, analyzed, and compared in terms of settling time and overshoot. The simulation results are subdivided in the subsequent sections.

4.1 Direct Online and Soft Starter Rotor Speed Result

The rotor speed at transient states which reflect the difference in starting methods between a DOL starter and a soft starter are analyze shown in this section. The rotor speed responses are presented in Figs. 4 to 8.

The transient time of rotor speed of direct online and soft starter at 0% of the rated load is shown in Fig 4, direct. Online starter (DOL) reaches it transient state at 0.3 seconds while that of soft starter is 0.2 seconds.

At 25% load, transient time of direct online is 0.5 seconds while soft starter is 0.3 second as seen in Fig. 5.

At 50% load, transient time of direct online is 0.7 seconds while soft starter is 0.5 second as seen in Fig. 6.

At 75% load, transient time of direct online is 1.4 seconds while soft starter is 0.9 second as seen in Fig. 7.

At 100% load, transient time of direct online is 1.6 seconds while soft starter is 1.1 second as seen in Fig. 8.

Table 2 shown the summary of comparison between direct online starter and soft starter of rotor speed.

4.2 Direct Online and Soft Starter Electromagnetic Torque Result

The electromagnetic torque transient states which reflect the difference in starting methods between a DOL starter and a soft starter are analyze below. The responses of electromagnetic torque are presented in Figs. 9 to 13.

At 0% load, transient time of direct online is 0.4 seconds while soft starter is 0.3 second as seen in Fig. 9.

At 25% load, transient time of direct online is 0.5 seconds while soft starter is 0.4 second as seen in Fig. 10.

At 50% load, transient time of direct online is 0.8 seconds while soft starter is 0.5 second as seen in Fig. 11.

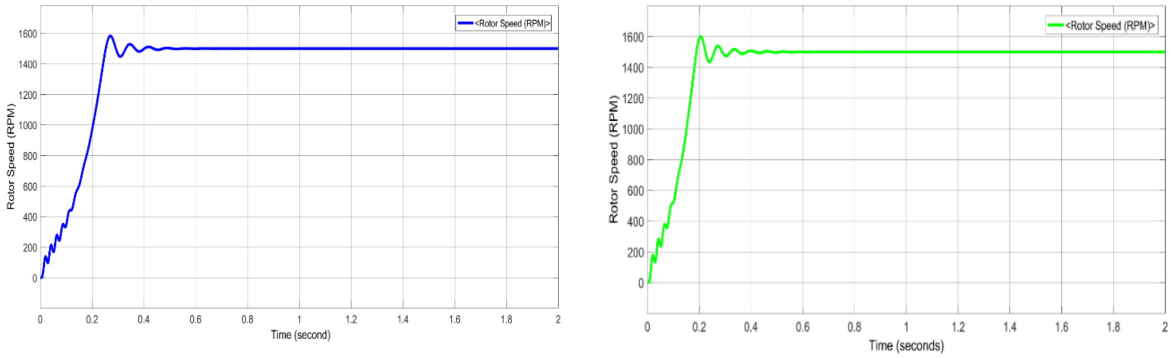
At 75% load, transient time of direct online is 1.5 seconds while soft starter is 1.2 second as seen in Fig. 12.

Table 2. DOL and Soft starter transient time simulation results on rotor speed.

Load %	DOL transient time (sec)	Soft Starter transient time (sec)
0%	0.3	0.2
25%	0.5	0.3
50%	0.7	0.5
75%	1.4	0.9
100%	1.6	1.1

Table 3. DOL and Soft starter transient time simulation results on electromagnetic torque

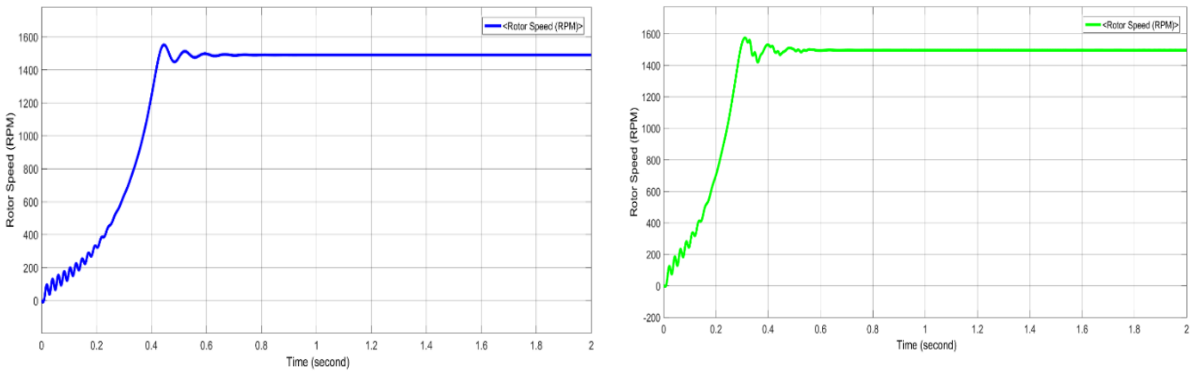
Load %	DOL transient time (sec)	Soft Starter transient time (sec)
0%	0.4	0.3
25%	0.5	0.4
50%	0.8	0.5
75%	1.5	1.2
100%	1.7	1.5



DOL

Soft starter

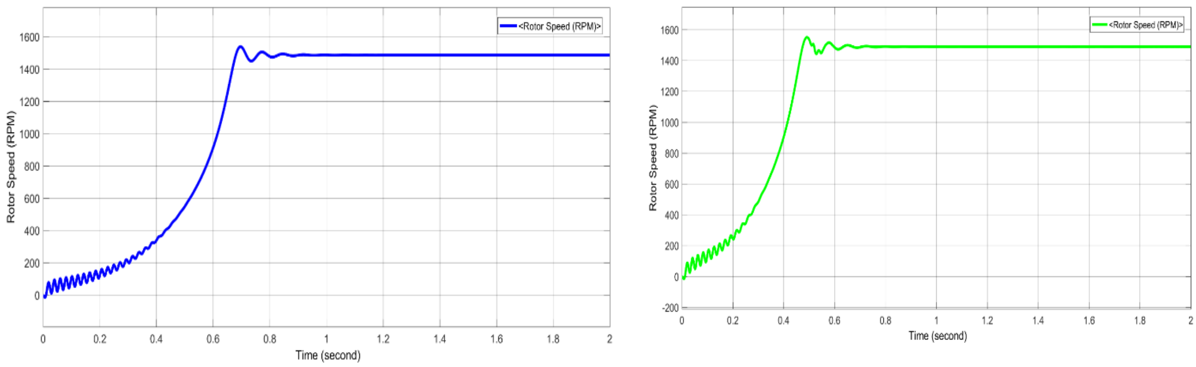
Fig. 4. Direct online and soft starter rotor speed at 0% load (0 N*m)



DOL

Soft starter

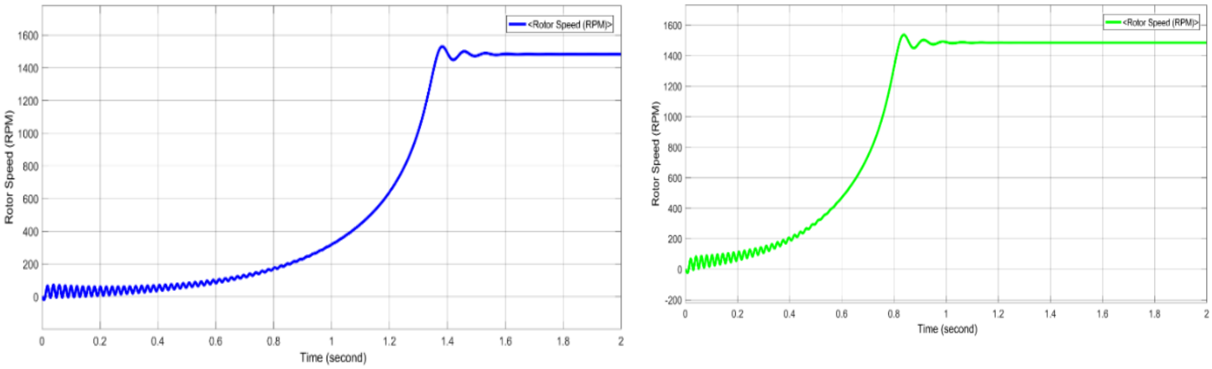
Fig. 5. Direct online and soft starter rotor speed at 25% load (60 N*m)



DOL

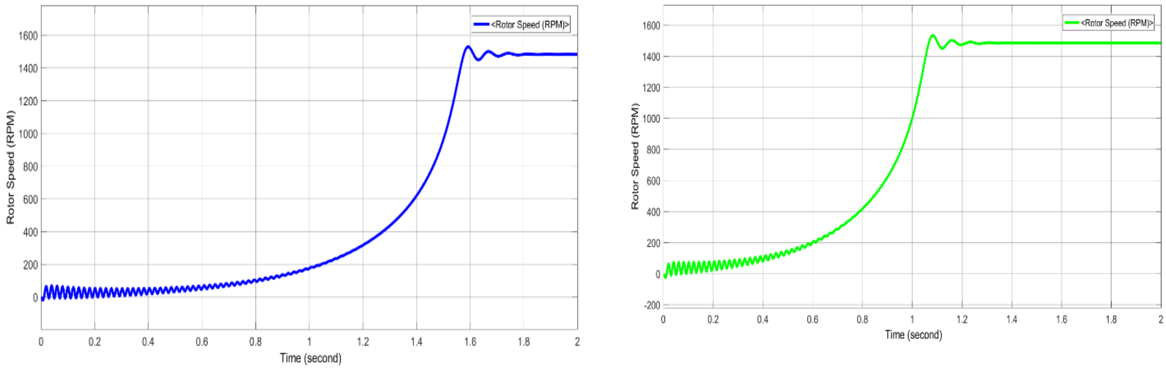
Soft starter

Fig. 6. Direct online and soft starter rotor speed at 50% load (119 N*m)



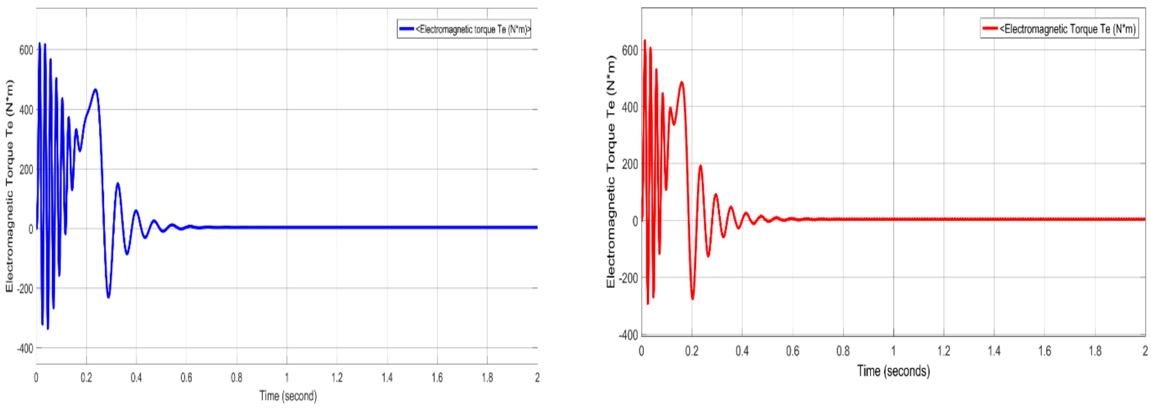
DOL Soft starter

Fig. 7. Direct online and soft starter rotor speed at 75% load (179 N*m)



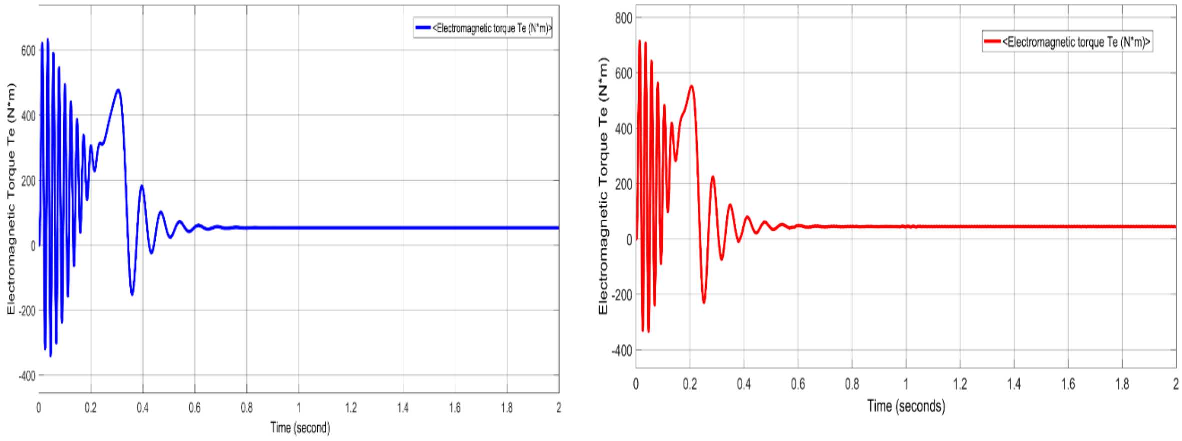
DOL Soft starter

Fig. 8. Direct online and soft starter rotor speed at 100% load (238 N*m)



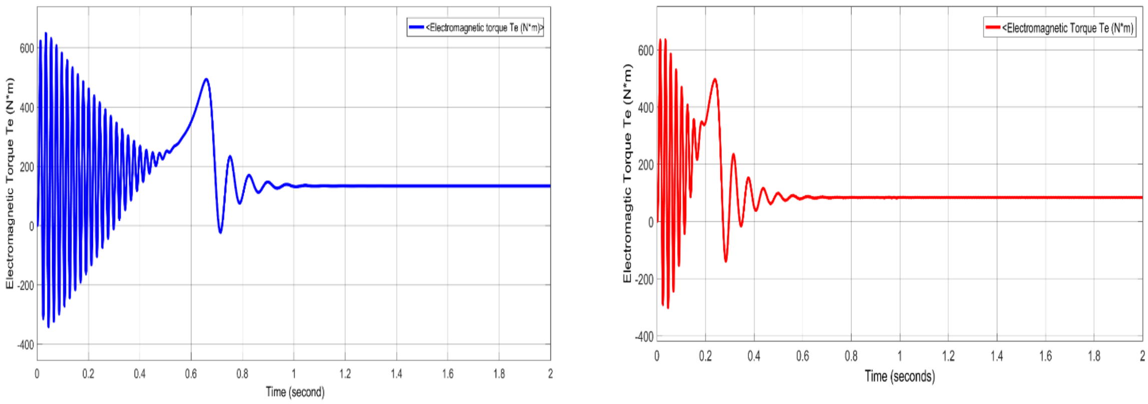
DOL Soft starter

Fig. 9. Direct online and soft starter electromagnetic torque at 0% load (0 N*m)



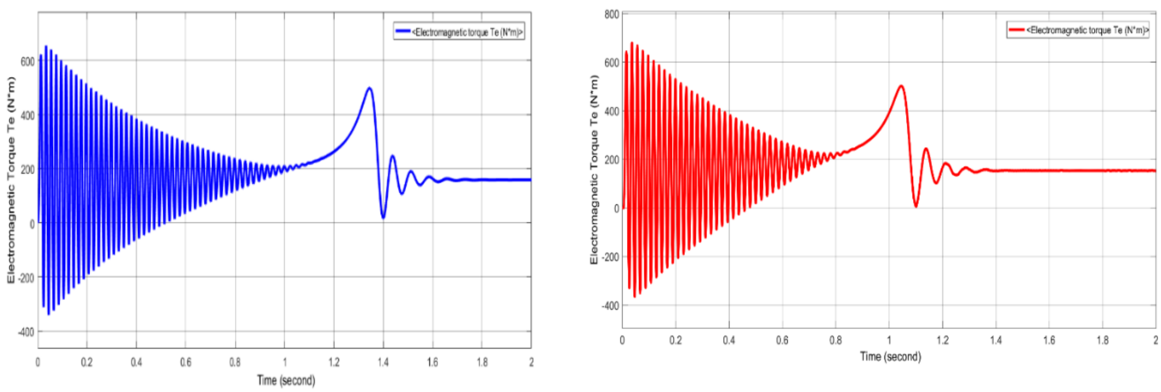
DOL Soft starter

Fig. 10. Direct online and soft starter electromagnetic torque at 25% load (60 N*m)



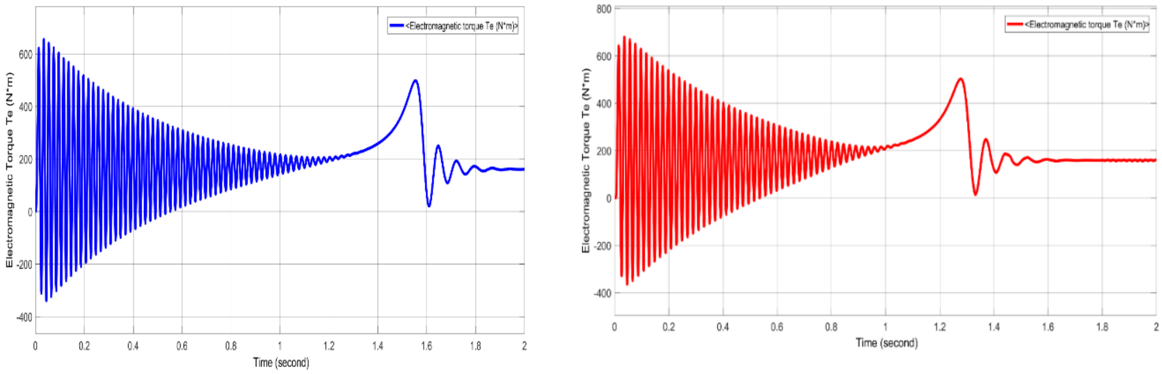
DOL Soft starter

Fig. 11. Direct online and soft starter electromagnetic torque at 50% load (119 N*m)



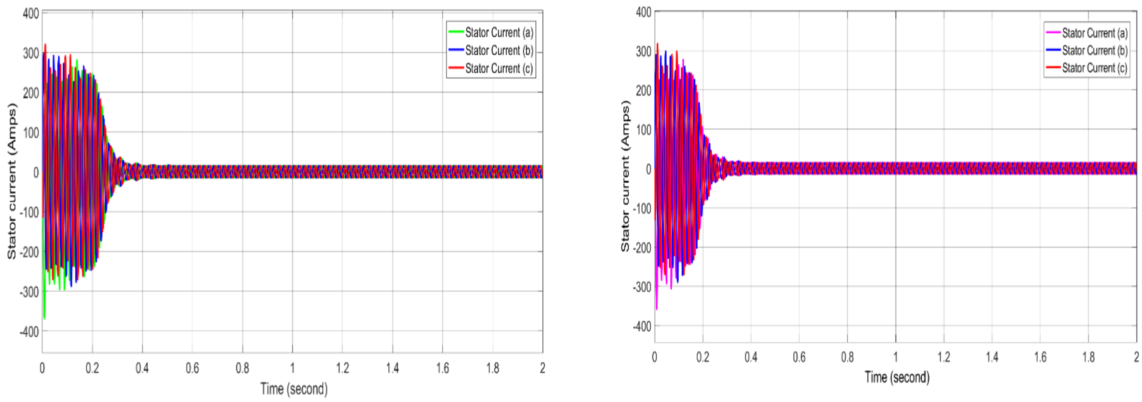
DOL Soft starter

Fig. 12. Direct online and soft starter electromagnetic torque at 75% load (179 N*m)



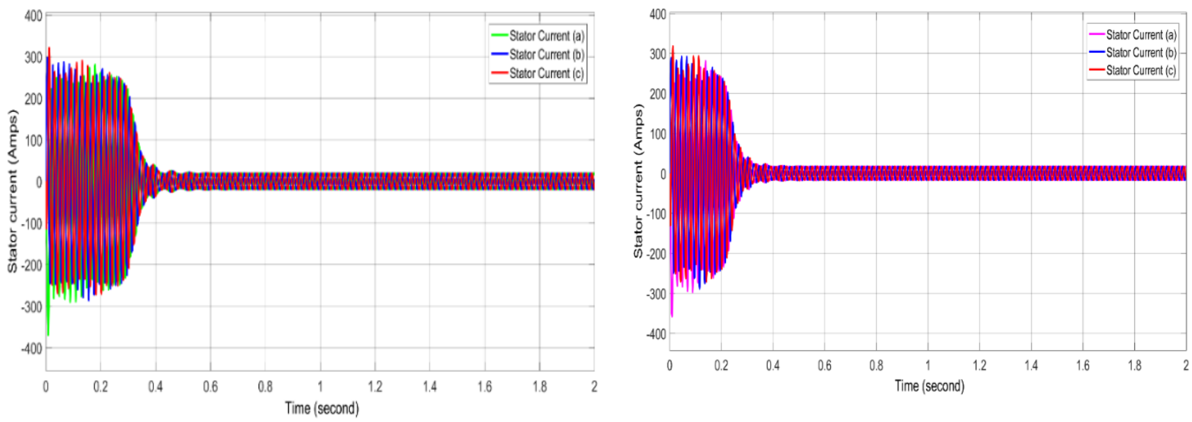
DOL Soft starter

Fig. 13. Direct online and soft starter electromagnetic torque at 100% load (238 N*m)



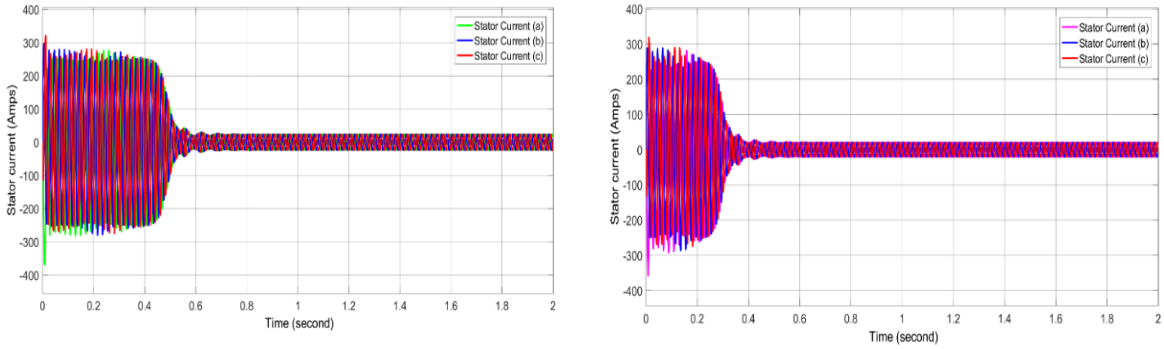
DOL Soft starter

Fig. 14. Direct online and soft starter stator current at 0% load (0 N*m)



DOL Soft starter

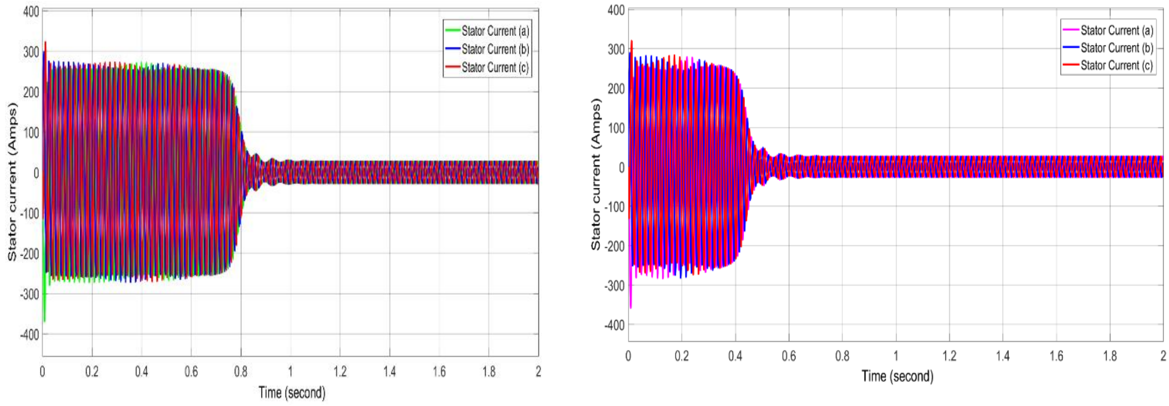
Fig. 15. Direct online and soft starter stator current at 25% load (60 N*m)



DOL

Soft starter

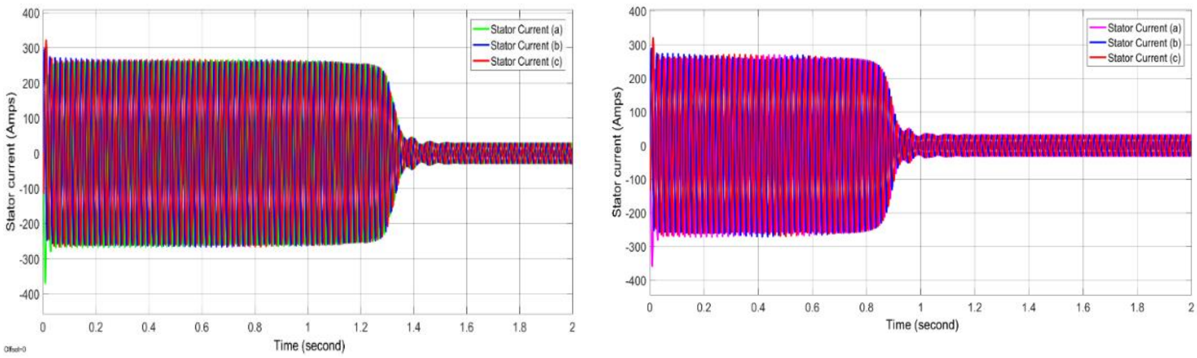
Fig. 16. Direct online and soft starter stator current at 50% load (119 N*m)



DOL

Soft starter

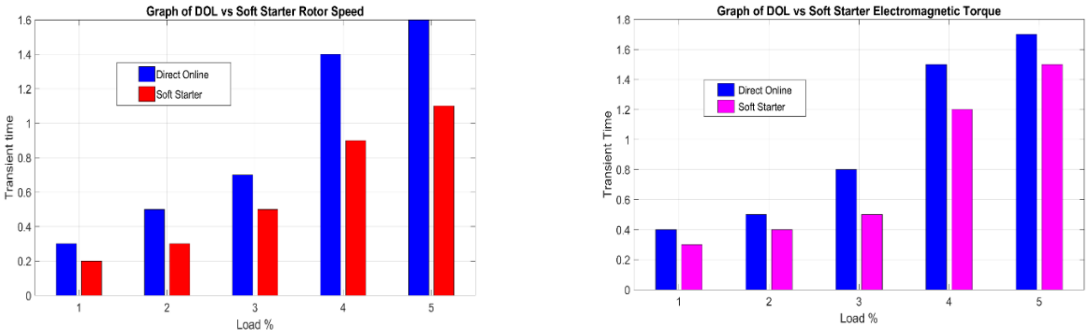
Fig. 17. Direct online and soft starter stator current at 75% load (179 N*m)



DOL

Soft starter

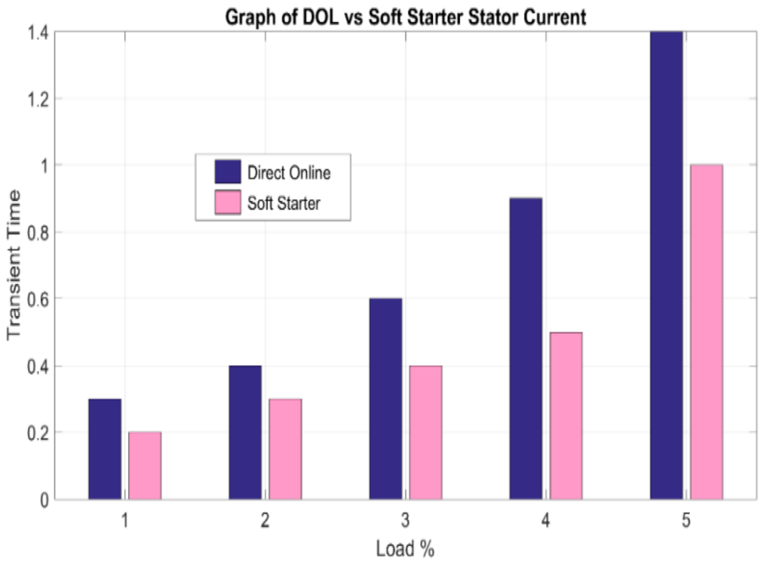
Fig. 18. Direct online and soft starter stator current at 100% load (238 N*m)



Rotor Speed

Electromagnetic Torque

Fig. 19. Direct online and soft starter Rotor speed and Electromagnetic torque



Stator Current

Fig. 20. Direct online and soft starter Rotor speed and Electromagnetic torque

Table 4. DOL and Soft starter transient time simulation results on stator current

Load %	DOL transient time (sec)	Soft Starter transient time (sec)
0%	0.3	0.2
25%	0.4	0.3
50%	0.6	0.4
75%	0.9	0.5
100%	1.4	1.0

At 100% load, transient time of direct online is 1.7 seconds while soft starter is 1.5 second as seen in Fig. 13.

Table 3 shown the summary of comparison between direct online starter and soft starter of electromagnetic torque.

4.3 Direct Online and Soft Starter Stator Current Result

The stator current transient time of both the direct online starter and soft starter are shown in Figs. 14 to 18. Direct online starter with high inrush current causes the voltage to dips they by stressing the electrical components. Soft Starter reduced the high inrush current and minimizes the voltage dips and electrical stress.

At 0% load, transient time of direct online is 0.3 seconds while soft starter is 0.2 second as seen in Fig. 14.

At 25% load, transient time of direct online is 0.4 seconds while soft starter is 0.3 second as seen in Fig. 15.

At 50% load, transient time of direct online is 0.6 seconds while soft starter is 0.4 second as seen in Fig. 16.
At 75% load, transient time of direct online is 0.9 seconds while soft starter is 0.5 second as seen in Fig. 17.

At 100% load, transient time of direct online is 1.4 seconds while soft starter is 1.0 second as seen in Fig. 18.

The direct comparison is shown in graph of DOL and Soft Starter Rotor speed, Electromagnetic torque and Stator current represented in Figs. 19 and 20.

5. CONCLUSION

In this study, the transient effects of a three-phase induction motor using both Direct Online (DOL) and Soft Starter methods were analyzed. The modeling and simulation were done using MATLAB/Simulink software. The simulation models were meticulously developed to capture the dynamic behavior of the motor during startup, allowing for an in-depth analysis of the different starting load torque.

The results from the simulation indicate a stark contrast in performance between the DOL and Soft Starter methods. The DOL starter, while simple and cost-effective, exhibited significant inrush currents and torque transients, leading to mechanical and electrical stresses on the motor and associated equipment. This method, although widely used, can result in substantial wear and tear, reducing the lifespan of the motor and increasing maintenance requirements.

Conversely, the Soft Starter demonstrated a more controlled and gradual increase in voltage, leading to a substantial reduction in inrush current and smoother torque transition.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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