RESEARCH ARTICLE

SAMRIDDHI Volume 14, Issue 4, 2022 Print ISSN: 2229-7111 Online ISSN: 2454-5767

Performance analysis of Average-value based modeling of Field-oriented-controlled Induction Motor Drive System in real-time environment

Vivek Pahwa

Assistant Professor, Department of Electrical and Electronics Engineering, UIET, Panjab University, Chandigarh, India.

Abstract

Appropriate modeling plays an important role for analyzing the behavior of any system for its particular application. Therefore, in this work, average modeling of three-phase squirrel cage induction motor and three-phase pulse-width modulated inverter is proposed and used for analyzing the dynamic control performance of induction machine drive system using field-oriented-control strategy for reducing the computational effort in MATLAB/SIMULINK environment, also termed as offline environment. The rotor reference frame is used for inverter as well as for induction machine. The simulation results obtained with this proposed model is compared with well established detailed model. This comparison reveals that the computational time is reduced 10 times approx. while showing the similar control performance of the drive system with this proposed technique. Further, this proposed model is transformed into real-time model using FPGA based simulator i.e. OPAL RT-4510 for its validation as well as for its practical implementation.

Keywords: Average value based modeling, field-oriented-controlled induction machine drive system, offline and online environments.

SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology (2022); DOI: 10.18090/samriddhi.v14i04.30

Introduction

Induction machine (IM) drive system has become the most preferred choice in comparison to Direct Current machine drive system. It is due to active research in the field of power electronic devices, advancement in control strategies and inherent features of induction motor like ruggedness, less maintenance and self starting.[1-4] However, it is a singly-excited system; therefore the dynamic control of this motor is complex.[5]

In,[6] scalar and vector control strategies of 3-phase induction machine have been developed and analyzed. Although scalar control strategies, have given adequate steady-state performance, but these do not provide satisfactory transient performance.[1,2] Later on, advanced schemes such as direct torque control[7] and field oriented control techniques[8-10] were developed and well suited for transient as well as for steady state analysis. Among these two, field oriented control is comparatively easy to implement.[10] Therefore, this control is selected for this work.

For proper implementation of any control strategy on any practical system, appropriate modeling plays a very crucial role. There are two ways to model the induction motor *i.e.* equivalent circuit approach and two-axis theory.[1,2] The former is suitable for steady-state analysis and latter approach is suitable for steady-state as well as for transient analysis. Thus, two-axis theory based approach gives the complete solution for analyzing the dynamic performance of this machine. This approach can be implemented through arbitrary reference frame. There are three types of reference frames such as synchronously rotating reference frame, rotor reference frame and stator reference frame. The selection of a particular reference frame depends upon its application.

Therefore it is essential to analyze this control strategy to understand its control effort accurately. Electromagnetic transient simulations are performed to study this control using MATLAB/SIMULINK environment.[11] In this environment, detailed model of inverter, induction machine and its associated components is used. This model gives accurate results at the cost of increased computational burden,

Corresponding Author: Vivek Pahwa, Assistant Professor, Department of Electrical and Electronics Engineering, UIET, Panjab University, Chandigarh, India, e-mail: v1974pahwa@gmail.com

How to cite this article: Pahwa, V. (2022). Performance analysis of Average-value based modeling of Field-oriented-controlled Induction Motor Drive System in real-time environment. *SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology,* 14(4), 170-175.

Source of support: Nil

Conflict of interest: None

resulting into reduced simulation speed. This burden is increased due to handling of switching associated with inverter. However, these switching are not essential for analyzing the performance of any control strategy.

The solution to this limitation is achieved by converting this model to average value model.[2,12,13] While doing so, all the switching events are averaged out, and operation of inverter is represented by a set of algebraic equations.

Most of the work addressed above has been developed in offline environment. In,[14] a detailed model of induction machine is developed in MATLAB/SIMULINK. Depending upon the model extensiveness, this environment produces the voltage/current signals of the model which are not in synchronism with the real-time clock. Hence, the practical implementation of the model developed in this environment is very difficult.

In recent times, it is possible to develop any model in online environment using any FPGA based real-time simulator like *OPAL RT*.[15] Due to inherent advantages associated with FPGA like parallel-processing and very small time step size in the order of 250 nanoseconds, this simulator produces the signals which are in synchronism with the real-time clock. Therefore, in this work this platform has been used for its practical implementation.

Therefore, in this work, average-value modeling of a field-oriented-controlled induction machine drive system is developed in *MATLAB/SIMULINK* environment using two-axis theory with rotor reference frame for inverter as well as for induction machine. The comparison of this model with detailed model gives the superiority of this modeling technique in terms of computational burden while keeping intact the control performance. The proposed model has been developed in offline environment. Then, it is transformed into real time environment using OPAL RT-4510 simulator for its practical implementation.

System Description

The induction machine drive system shown in Figure 1 consists of four major parts i.e. a) rectifier with chopper, b) three-phase inverter (average value), c) three-phase induction machine and at last d) field-oriented control block.

The function of first block i.e. rectifier with chopper is to convert the three-phase 415 V, 60 Hz supply (fixed) to variable DC voltage, v_{dc}. Then, this variable DC voltage is applied to next block i.e. average value based inverter to convert this DC supply to variable AC supply. The inverter assumed here is lossless. Therefore, input instantaneous power, P_{in} is equal to output instantaneous power, P_{out} of the inverter *i.e.*

$$P_{in} = P_{out} \qquad (1)$$

Where $P_{in}=v_{dc}\, i_{dc}$ and $P_{out} = 1.5(\, v_{qs}i_{qs} \times v_{ds}i_{ds})$. Putting these two power terms in equation (1), we will get:

$$v_{dc}i_{dc} = 1.5(\, v_{qs}i_{qs} \times v_{ds}i_{ds}) \qquad (2)$$

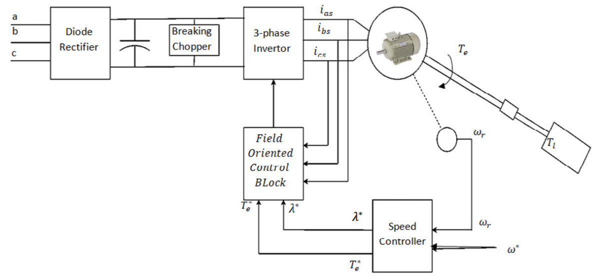


Figure 1: Field oriented controlled induction machine drive system

It is to be noted here that the output voltages generated by the inverter are v_{qs} and v_{ds} which are instantaneous in nature. As the purpose of this paper is to study the induction machine dynamics, therefore, it is essential to convert these instantaneous voltages to its equivalent average value based voltages i.e. $\bar{v}_{qs}$ & $\bar{v}_{ds}$[2] and these are:

$$\bar{v}_{qs} = kv_{dc} \text{ and } \bar{v}_{ds} = 0 \qquad (3)$$

Where, k is the duty cycle of the inverter. Its value depends upon the modulation technique used for inverter switching.

Now, these average value based variable AC supply is applied to the three-phase squirrel cage induction machine. The induction machine model in rotor reference frame [Vivek Pahwa] can be given as;

$$\begin{bmatrix} \bar{v}_{qs} \\ \bar{v}_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + \frac{dL_s}{dt} & \omega_r L_s & \frac{dL_m}{dt} & \omega_r L_m \\ -\omega_r L_s & R_s + \frac{dL_s}{dt} & -\omega_r L_m & \frac{dL_m}{dt} \\ \frac{dL_m}{dt} & 0 & R_r + \frac{dL_r}{dt} & 0 \\ 0 & \frac{dL_m}{dt} & 0 & R_r + \frac{dL_r}{dt} \end{bmatrix} \begin{bmatrix} \bar{\imath}_{qs} \\ \bar{\imath}_{ds} \\ \bar{\imath}_{qr} \\ \bar{\imath}_{dr} \end{bmatrix} \qquad (4)$$

The electromagnetic torque, *T* developed by the machine is

$$\bar{T} = 1.5\frac{P}{2}(\bar{\imath}_{qs}\bar{\imath}_{dr} \times \bar{\imath}_{ds}\bar{\imath}_{qr}) \qquad (5)$$

The load torque and machine interaction equation can be given as

$$\bar{T} - T_L = J\frac{d\omega_r}{dt} \qquad (6)$$

The function of third block i.e. field-oriented-controller is to fed the controlled signals to inverter as well as to the chopper. For deriving the equations related to field-oriented-control, the stator and rotor flux equations on d-q axis can be given as:

$$\bar{\varphi}_{sd} = L_s\bar{\imath}_{sd} + L_m\bar{\imath}_{rd} \qquad (7)$$

$$\bar{\varphi}_{sq} = L_s\bar{\imath}_{sq} + L_m\bar{\imath}_{rq} \qquad (8)$$

$$\bar{\varphi}_{rd} = L_r\bar{\imath}_{rd} + L_m\bar{\imath}_{sd} \qquad (9)$$

$$\bar{\varphi}_{rq} = L_r\bar{\imath}_{rq} + L_m\bar{\imath}_{sq} \qquad (10)$$

For decoupling the control variables of induction machine [1, 5], the rotor flux component on q-axis must be zero, therefore, its derivative will also becomes zero and are given below.

$$\bar{\varphi}_{rq} = 0 \qquad (11)$$

$$\frac{d\bar{\varphi}_{rq}}{dt} = 0 \qquad (12)$$

Therefore, rotor flux will have d-axis component only and given as:

$$\bar{\varphi}_{rd} = \bar{\varphi}_r \qquad (13)$$

Which implies

$$\omega_{sl} = \frac{L_m}{L_r}\frac{R_r \bar{\imath}_{sq}}{\bar{\varphi}_r} = (\omega - \omega_r) \qquad (14)$$

Now, the electromagnetic torque, $\bar{T}_e$ developed by the field-oriented-controlled Induction machine is

$$\bar{T}_e = 1.5p\frac{L_m}{L_r}(\bar{\varphi}_r \bar{\imath}_{sq}) \qquad (15)$$

Therefore, the rate of change of rotor flux can be represented as

$$\frac{d\bar{\varphi}_r}{dt} = -\frac{R_r}{L_r}(\bar{\varphi}_r) + \frac{L_m R_r}{L_r}(\bar{\imath}_{sd}) \qquad (16)$$

It is to be noted here that this rotor flux has two components i.e. flux and torque component, which resembles with the DC machine. Thus the field-oriented-controlled induction machine will give the same response as that of DC machine.

Results and Discussions

The model of average-value based inverter fed field-oriented-controlled induction machine drive system has been developed in previous section and then it is implemented in MATLAB/SIMULINK environment. The parameters of induction machine are given in appendix.[1]

Initially, the drive system is started with a load torque of 392 Nm and the rotor speed is ramping from zero rpm to 500 rpm. While speed is ramping, the load torque is further increased to 792 rpm at 0.5 second. At 0.6 second, the speed is stable at 500 rpm and the system is able to withstand the applied load torque of 792 Nm. At 1 second, the speed is reduced to zero in ramped manner. And, at the same time the torque is reduced to 450 Nm. At 1.5 seconds, the rated load torque is applied in negative direction. The total run time is 3 seconds.

The same simulation scenario is applied on the detailed version of this model. The important variables in superimposed form are shown in Figures 2 to 5 for analysis of these models.

Figure 2 shows stator 'a' phase current, electromagnetic torque, rotor speed, and DC bus voltage. From the waveform of phase 'a' current, it can be seen that the pattern of both the waveforms are same from control point-of-view. However, there are more ripples in the current due switching action of the inverter with detailed version. In contrast, there are no ripples with average model, due to averaging effect. From equation (5), it is clear that the electromagnetic torque is directly related with stator current; therefore, the similar behavior is there also. In other words, there are ripples with detailed model and no ripples with proposed model.

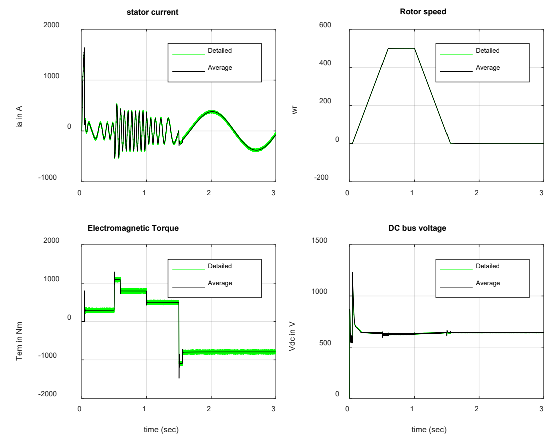


Figure 2: Phase 'a' stator current, rotor speed, electromagnetic torque and DC bus voltage with both the models in offline environment.

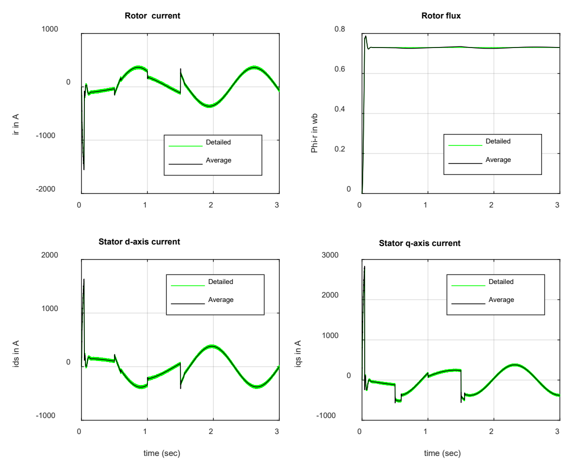


Figure 3: Phase 'a' rotor current, rotor flux, stator d- and q-axis currents with both the models in offline environment

Practically, mechanical time-constant is very large in contrast to electrical time-constant of the inverter switching. Therefore, rotor speed, , is not averaged (refer equation (4)), resulting into same behavior with both the models.The DC bus voltages are also same with both the models and are constant at 650 V, showing the effective control of chopper system.

Comparision of variables like rotor phase 'a' current, rotor flux and d- and q-axis rotor currents is shown in Figure 3. Rotor current is a part of stator current, therefore, rotor currents have explanation from ripples and control performance point-of-view as already discussed in Figure 2. Apart from these following are the major observations;

- Similar pattern is there for i_{ar}, i_{qr} and i_{dr}, which shows that rotor reference frame has been chosen for inverter as well as for inverter.

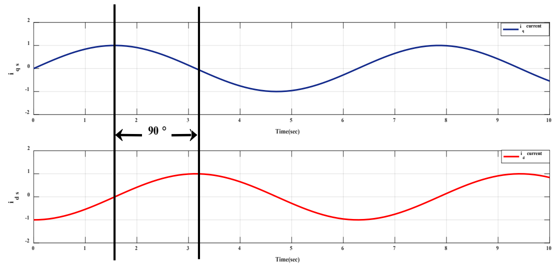


Figure 4: Stator d- and q-axis currents w.r.t. time with both the models in offline environment

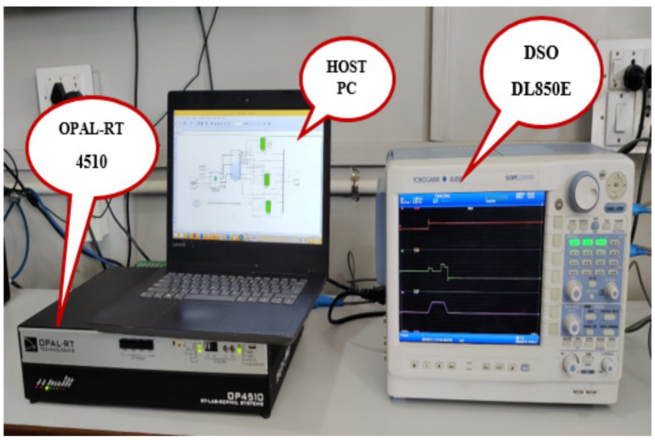
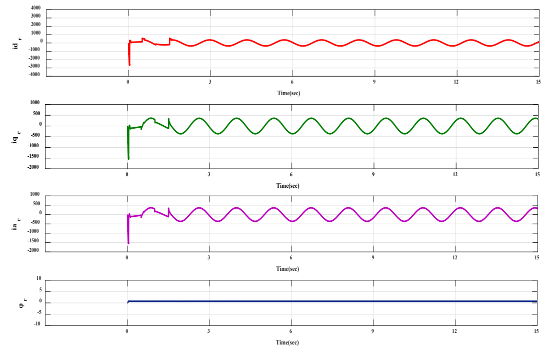


Figure 5: Experimental set-up for transformation from offline to online environment

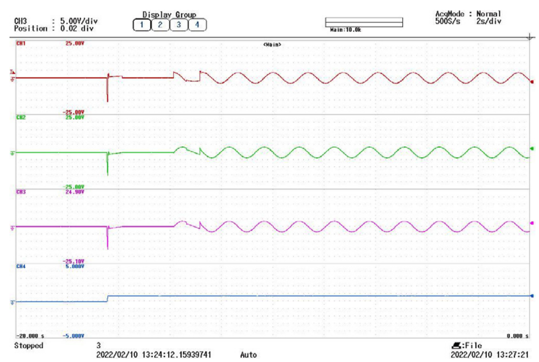
- During whole simualtion period there is negligible change in rotor flux, with an exception at starting. This shows the superior transient performance of field-oriented-control.

The stator d-axis and q-axis currents have been shown in Figure 4. It can be observed from these figures that these currents are changing as per rotor frequency. However, zoomed view of these two currents during steady-state shows that these 90 degrees apart from each other. It means that the field-oriented-control is effectively decoupling these highly coupled variables i.e. flux and torque.

The analysis accomplished till now, reveals that the average model based drive system is capable of keeping intact the control dynamics, which is the main purpose of this work. Now, this offline model has been transformed into online model using FPGA based real-time simulator i.e. OPAL-RT 4510 for its practical implementation. The conversion and its implementation in detail are given in reference [*Preeti et. al*.]. The experimental set-up used is shown in Figure 5.



(a)



(b)

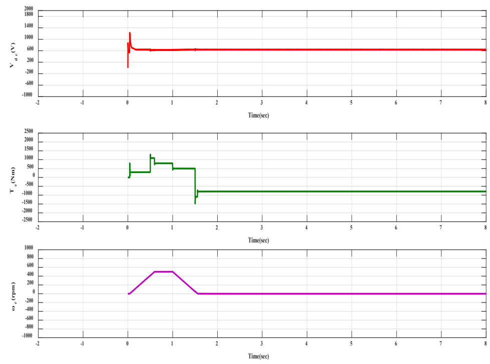
Figure 6: d-axis rotor current, q-axis rotor current, phase-a rotor current and rotor flux in (a) offline and (b) online environment

The MATLAB/SIMULINK environment is called as offline environment, whereas, the latter one is called as online environment. Now, the simulation is run for 15 seconds. Number of variables of the drive system in offline and online mode is shown in Figure-6 and 7. It is to be noted here that although the pattern of wave-shapes is same, but there is huge difference in execution time of these two models and environments (refer Table 1).

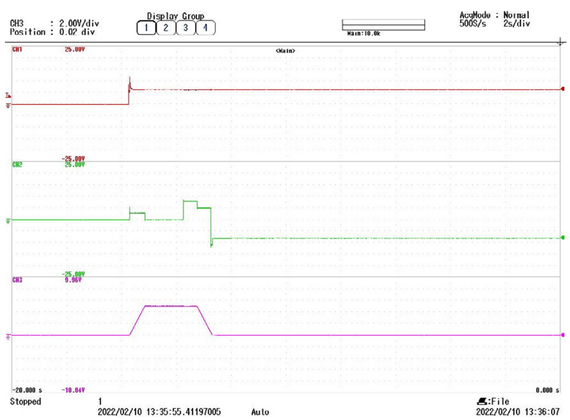
The analysis of Table 1 reveals that in offline mode for 3 seconds of simulation time or real clock time, the detailed model takes 66 seconds for its execution, whereas, average model takes 5 seconds. Although the proposed model reduces the computation burden by 10 times in comparison to its detailed version, but still it is not suitable for its real time implementation. Therefore, this proposed model has been converted from offline version to its online version.

Table 1: Execution time of the two models in online and offline modes

S. no.	*Real clock time*	*Computation time*			*Remarks*
		Offline mode		*Online mode*	
		Detailed model	*Average model*	*Average model*	
1.	3 Seconds	66 Seconds	5 Seconds	3 Seconds	Clock synchronized signal with average model in online mode



(a)



(b)

Figure 7: DC bus voltage, electromagnetic torque and rotor speed in (a) offline and (b) online environment.

And it can be seen that real-time clock is synchronized with average model in online mode. In other words, real time clock is exactly same to that of the computation time i.e. 3 seconds.

Conclusions and Future Scope of The Work

Following are the major conclusions of this work.

- The comparison of the average value based model of inverter with its detailed version reveals that the dynamics of the system remains intact and at the same time the computation burden is reduced by ten times (approximately) with the proposed model.
- The dynamics of stator current and electromagnetic torque is same with both the models. However, more ripples are there in these two quantities due to switching of inverter with detailed modeling in comparison to proposed model. And, the behavior of speed and DC bus voltage is also same.

Rotor reference frame is found to be suitable for implementation of field oriented control strategy on induction machine; therefore, same reference frame is used for inverter for accurate control of overall system. The similar pattern of rotor phase 'a' current and rotor q-axis current strengthens this fact.

Once the above conclusions have been drawn on the basis of the simulation results using offline environment i.e. MATLAB/SIMULINK environment. It is to be noted here that, although, the computation burden has been reduced significantly, but still it is not synchronized with the real- time clock. Thus, its practical is not possible. Therefore, the model is transformed into real-time model using OPAL-RT simulator for its practical implementation. The clock synchronized operation of the system also validates the proposed average-value based model of the drive system.

On the basis of successful implementation of this average modeling on induction motor drive system, it is recommended to implement this modeling on similar kind of systems like 3-phase and 5-phase permanent magnet synchronous machine drive systems.

Acknowledgement:

The author acknowledges the support of Design Innovation Centre (DIC) sponsored by MHRD under sub-theme "Energy Harvesting and Management Technology" for providing the necessary financial aid and laboratory facilities for the completion of this work.

References

[1] Bose, Bimal K. "Power electronics and AC drives." *Englewood Cliffs*,1986.

[2] P.C. Krause, "Analysis of electrical machines and drive systems" Prentice Hall, 1985.

[3] P.S. Bhimbhra," Generalized Theory of Electrical machines", Eighth Edition Khanna Publishers, Delhi.

[4] Dubey, Gopal K. "Power semiconductor-controlled drives." *Power semiconductorcontrolled drives*,1989.

[5] Ho, Edward YY, and Paresh C. Sen. "Decoupling control of induction motor drives." *IEEE Transactions on Industrial Electronics* 35, no. 2 (253-262),1988.

[6] Zidani, Fatiha, Med-Said Nait-Said, Rachid Abdessemed, and Azeddine Benoudjit. "Induction machine performances in scalar and field-oriented control." In *POWERCON'98. International Conference on Power System Technology. Proceedings (Cat. No. 98EX151)*, vol. 1, pp. 595-599, 1998.

[7] Vas, Peter. *Sensor less vector and direct torque control*. Vol. 42. Oxford, [Eng.]; New York: Oxford University Press, 1998.

[8] Tajima H, Hori Y. Speed sensor less field-orientation control of the induction machine. IEEE Transactions on Industry Applications. 1993 Jan;29(1):175-80.

[9] Singh, Bhim, B. N. Singh, B. P. Singh, Ambrish Chandra, and Kamal Al-Haddad. "Unity power factor converter-inverter fed vector-controlled cage motor drive without echanical speed sensor." In *Proceedings of IECON'95-21st Annual Conference on IEEE Industrial Electronics*, vol. 1, pp. 609-614, 1995.

[10] Lakaparampil, Z. V., K. A. Fathima, and V. T. Ranganathan. "Design, modelling, simulation and implementation of vector-controlled induction motor drive." *Proceedings of International Conference on Power Electronics, Drives and Energy Systems for industrial Growth*. Vol. 2, 1996.

[11] The Math works, Inc. MATLAB, Version 2020a.

[12] Liu, Xiao, Aaron M. Cramer, and Fei Pan. "Generalized average method for time-invariant modeling of inverters." *IEEE Transactions on Circuits and Systems I: Regular Papers* 64.3 (740-

751),2016.

[13] Ahmed S, Boroyevich D, Wang F, Burgos R. Development of a new voltage source inverter (VSI) average model including low frequency harmonics. In2010 Twenty Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2010.

[14] Ozpineci, Burak, and Leon M. Tolbert. "Simulink implementation of induction machine model- A modular approach." In *IEEE International Electric Machines and Drives Conference, 2003. IEMDC'03.*, vol. 2, pp. 728-734, 2003.

[15] A. Mohanty, M. Viswavandya, P. K. Ray and S. Mohanty, "Literature survey on OPAL-RT Technologies with Advance features and Industrial applications," 2018 1st International Conference on Advanced Research in Engineering Sciences (ARES), 2018, pp. 1-5, doi: 10.1109/ARESX.2018.8723268, 2018.

Appendix[1]

Table 2: The parameters of the motor are [19]:

Parameters	*Motor Specifications*
Nominal Power, P	*149 kW*
Rated voltage, V	*460 V (line to line)*
Rated frequency, f	*60 Hz*
Poles, p	*4*
Connection	*Delta*
Stator resistance, Rs	*14.85e-3 ohms*
Stator inductance, Ls	*0.327e-3 H*
Rotor resistance, Rr	*9.295e-3 ohms*
Rotor inductance, Lr	*0.327e-3 H*
Mutual inductance, Lm	*10.46e-3 H*
Moment of inertia, J	*3.1 Kgm2*
Friction factor, F	*0.08*