SENSORLESS SPEED CONTROL OF DOUBLY-FED INDUCTION MACHINE USING REACTIVE POWER BASED MRAS

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Abstract. A sensorless speed control method for doubly-fed induction machine (DFIM) operating with constant frequency but in variable speed mode is presented in this project work. The control method is based on rotor speed estimation technique by a reactive power model reference adaptive system (MRAS) observer. The presented technique does not depend on any kind of flux evaluation and also independent to the resistance variation of either stator or rotor. The MRAS observer has a capacity for speed catching operation. PI controller is designed and also optimized using algorithm for better dynamic behaviour of the machine. MATLAB Simulink model and the simulation results are shown to check the effectiveness of the observer and also of the controller.

1. Introduction
Now a days the area of electric drive have shown a lot of growth i.e. difficulties which are encountered in early days are easily removed due to the development in modern micro-electronics and also ac machines almost overtaken the field of variable speed applications which formerly was conquered by dc machine drives. [1] Especially in ac drives doubly fed induction machines are very popular in various applications such as where high power and wide range of speed is the main requirement. When supply is given to both stator and rotor of a three-phase IM then it is called as doubly fed induction machine. The DFIM can be operated as DFIG with variable speed for both independent and
grid-connected application. [2] In a DFIM drive supply given to the stator directly from the source but input to rotor is given by using a back to back converter which is also fed from the same source through necessary arrangement like transformers and inductors. The advantages of DFIM over squirrel-cage IM is that, the converters are connected with rotor circuit and for some decided speed limit it handles a power i.e. (slip power) which is very small value compared to the nominal power of the machine. [3] For speed control we have to know the rotor position of the drive for that previously position sensors are mounted on the rotor shaft. But the shaft sensors have many draw backs like cost of the system used to measure the speed maintain of the system difficulties in laying the cable between the sensor controllers. [4] Robustness of the speed measuring system all these difficulties can be avoided by eliminating the use of position encoder. Therefore sensor less vector control of DFIM drive has drawn a lot of attention now days. [5] A number of sensors less vector control method have been developed by using different technique. But all these provided technique have some drawbacks like the effect of machine parameters of the machine on the performance of the system which estimates the speed. Some of this technique has very complex calculations. [6] In some technique we need to estimate the flux, for this an integrator is used which cannot be perform the task at synchronous speed. To overcome all these problems of different technique MRAS observer which works by utilizing the reactive power is used to estimates slip speed. [7] To evaluate the slip speed MRAS employs a controller, also the power fed to the rotor to control the speed according to the requirement to be controlled by using a control strategy. [8]

2. Modeling of DFIM

DFIM is basically a slip ring induction machine having a stator and a rotor. Stator circuit of the machine consist of a laminated core type frame having slots for stator conductor. A balanced three-phase winding which is uniformly distributed over all slots with 1200 electrical displacement from each other. [9-14] These winding can be connected to form delta or stator circuit. The stator winding conductors are insulated from the core as well as from each other. The rotor circuit also has three-phase uniformly distributed winding housed in the rotor slots which are fixed with rotor core. [15-19] One end of the rotor winding connected in star manner and other side of rotor is connected to slip rings. The basic drive system using a DFIM is shown in the fig 1 given below.

![Basic DFIM Drive system](image)

**Figure 1. Basic DFIM Drive system**

The stator circuit connected to the source with soft starter to reduce the high inflow of current whenever required or sometimes it may be connected directly. Input to rotor circuit is also given from source by using an AC/DC/AC bidirectional converter. [20-22] This type converter consists of full bridge type converters connected through a DC-link in cascade. The converter rating used in DFIM is of 25-30 % of the rating of DFIM. Converter which control rotor input is named as rotor side converter (RSC), converter connected to source is named as source side converter (SSC). [23] Depending on the type of mode of operation converters may behave as rectifier or inverter. For these converters high speed switch is required so IGBT switches are implemented in these converters. The main function of RSC is to supply voltage to regulate the rotor current so that most of the rotor flux
will align in the direction of the stator flux to provide required torque. The main objective of SSC is to control the DC-link voltage; also it helps to maintain the quality of power by feeding reactive power when there is variation in reactive power. To operate the induction machine at its optimum efficiency is a difficult task their complex mathematical model and non-linear behaviour during the Saturation. Due to these factors the induction machine needs much effort to control. [24] So we need a high efficient control technique to control the induction machine. The problem in control like V/F control it cannot perform the task efficiently as it creates oscillations in the torque developed by the motor. To achieve a good dynamic performance vector control is done in induction machines. Vector control operation requires better knowledge about the transient behaviour of the machine which can do by studying the dynamic model of the machine. [25] For the control structure design the mathematical representation of machine should be like that it includes all the dynamic effect of both steady state and transient mode. The model of wound rotor induction motor when presented in d-q axis which are rotating at synchronous speed is derived by considering the position of axis as shown in fig 2.

![Figure 2. Schematic of axis transformation (ABC to dq)](image)

The d-axis which rotate at synchronous speed is shown in leading to phase A winding axis with an angle of $\theta_s$ and rotor phase-A axis is $\theta_r$ angle in leading to stator phase-A axis. The dynamic model of WRIM are presented by equivalent circuit diagrams as given below:

![Figure 3. Equivalent circuit diagram of WRIM w.r.t q-axis](image)

![Figure 4. Equivalent circuit diagram of WRIM w.r.t d-axis](image)

3. **Model Reference Adaptive System (MRAS)**

MRAS is an observer which evaluates the rotor speed of the machine using some quantities of the machine like power, rotor current, stator or rotor flux.
The basic structure of a MRAS resembles as showed in above figure. The model reference system utilizes two autonomous machine models of various structures to assess a comparative variable. The structure that does not include the variable that ought to be assessed, for example speed of rotor is considered as a kind of perspective or reference model. [5] Notwithstanding the structure which includes the variable to be evaluated is treated as a movable or adjustable model. The difference between the results of the two calculation blocks (see fig 5) is utilized to create a reasonable adaptive system. The distinction between the results of the perspective model and the output of the movable model winds up zero when the speed is effectively accessed. The evaluated rotor speed is at that point equivalent to the genuine machine speed. For our situation a PI controller is utilized to ensure the best possible adjustment, anyway consistent gain is also very famous. [1-4]

![Figure 5. Flowchart of MRAS Observer](image)

**Figure 5. Flowchart of MRAS Observer**

Reactive power based MRAS (Q-MRAS) estimate the slip speed, by the use of this value we can calculate the rotor speed. In this MRAS reference model calculate the instantaneous reactive power($Q_1$) from the d-axis and q-axis voltage current. The adjustable model used to calculate the actual reactive power($Q_4$) at steady state operation of the machine, by using machine parameter like resistance, inductance, magnetizing stator current, d-axis, q-axis current of the rotor and finally also the speed of the rotor is used in the calculation. Then the error ($\varepsilon = Q_1 - Q_4$) is given to the adaption mechanism which evaluates the slip speed ($\omega_{sl}$). The execution of control strategy using rotor current based MRAS observer shown in above figure 6 is quite easy due to the fact that rotor current is a measured quantity. In this type observer measured value of rotor current is compared with a estimated value of rotor current which is calculated from the voltage stator and current of the stator. This type of observer is works on the principle of adjustable model and reference model. Reference model means the evaluated rotor current $i_r$ which is filtered by using low-pass ant aliasing filter of second order. Adaptive model is the estimated value of rotor current from stator voltage and current. Then the error from the comparison of these two models is the cross product of the two outputs. So at the time of
normal operation the difference is zero as the phase co-ordination between the reference current of the rotor and measured rotor current is zero. MRAS based plans can likewise give flux estimation which can be helpful in vector control of Induction Motor drive. In this type control method flux model of both stator and rotor is used which based on the speed reference frame of the observer, the observer having this type modeling can be used in vector controlled Induction Motor drives as well as in the direct torque controlled (DTC) Induction Motor drives. Discrete-time direct torque control can be achieved by the use of this type adaptive flux observer. Basically the flux observer used for speed estimation by including an adaptive scheme which can estimates both states and unknown parameters. The adaptive scheme used here is derived by using Lyapunov theory. Compared to rotor current based observer in this observer the flux estimation error can be reduced much larger than the rotor current estimation error. In this observer speed estimation response can be improved by adding a proportional term. Disadvantages of Flux-observer based control drive are inefficient in low speed operation. This type observer operation depends on the resistance of both stator and rotor. [7][8]

4. Model Description
The main target of this project is to achieve speed control of doubly-fed induction machine without speed sensor or position sensor. Here a doubly fed induction generator for control purpose is taken into consideration. [26][27] From a three phase source input is given to the stator, also the rotor is connected to the same source through a converter, a dc link and an inverter, which are combined called as back to back converter. Both stator and rotor voltages, also the current first converted into 2 axis form i.e. abc to dq transformation is done for the use in MRAS observer. In this axis transformation angle reference is required which is calculated from the angular frequency of the stator. The basic block diagram of the the working model is shown below in figure 7.

![Figure 7. Basic Block Diagram of the System](image)

A mechanical torque reference is given to the machine to operate, by adjusting this reference torque we can also operate the machine as doubly fed induction motor. Other measurement are taken in per unit from the machine measurement port are stator current, rotor current, electromagnetic torque($T_{em}$) and also rotor speed ($\omega_r$) is measured. As it can be seen in the block diagram (figure 8) the input to the MRAS observer are d-q axis rotor voltage and current. Also stator magnetizing current is used in the MRAS observer which is calculated as per the expression provided in the theoretical development of MRAS. Reactive power based MRAS evaluate the slip speed, using this value rotor speed is estimated from synchronous speed. Also from the slip speed rotor angle is calculated which is used in the axis transformation. [9]
The estimated rotor speed is compared with a reference speed. The error from this comparison is used to calculate the reference value of q-axis current of the rotor using a PI controller. Then the reference q-axis current is compared with the actual value of q-axis current, and the error of this gives a reference rotor q-axis voltage again by the use of a PI controller. The d-axis rotor current reference value is calculated by comparing the actual rotor d-axis current with a small constant value. From the reference value of d-axis current d-axis reference voltage is evaluated using a PI controller. Finally, these 2-axis reference voltages are converted into three phase and is given as an input to the PWM generator which generates pulses accordingly to control the output of the inverter. Conventional proportional integral (PI) controller are designed and used in the model to control the output under variation like change in speed, change in load. The block diagram of the controller used in this system is shown below figure 9.

For improved dynamic response the employed controller is optimized using salp swarm optimization. The optimized gains of the different controller are presented in the table below:

### Table 1. Optimised Gain Value of Controller using SSA

| Name of the PI   | KP    | KI    |
|------------------|-------|-------|
| MRAS PI          | 5590.3254 | 9884.1793 |
| PI_wr            | 1781.1695 | 9121.3247 |
| ldr_PI           | 8549.4168 | 4560.5767 |
| lqr_PI           | 6310.7  | 7463.1343 |

### Table 2. Optimised Gain values Of controller Using ALO

| Name of the PI   | KP    | KI    |
|------------------|-------|-------|
| MRAS PI          | 1758.7321 | 2690.6432 |
| PI_wr            | 6476.215  | 4587.3582 |
| ldr_PI           | 5882.534  | 5447.256  |
| lqr_PI           | 4045.857  | 6962.736  |
The speed response curve with this optimization is compared with the speed response curve while using ALO optimization. This comparison is done to have the better dynamic behaviour with best optimised gain value.

5. Salp Swarm Algorithm
Salp swarm algorithm (SSA) for optimization is proposed by mirjalili. This optimization technique motivated from a creature called salp which belongs to salpidae family. This was based on salp’s swarming behaviour in deep ocean and this is done for having a good locomotion. Salp usually forms a chain called salp chain, all salp are divided into two groups: one is of leader and other comprises followers. Leader works as pilot in the chain and other follow their leader. This swarming behaviour of salp is mathematically modeled for solving optimization problems.

![Salp Algorithm Diagram](image)

Figure 10. Salp Algorithm

As in other swarm optimization method the location of salp is considered in an n-dimensional pursuit space, where ‘n’ is equal to the quantity of variables of the problem. So all the salp position is saved in a matrix of two dimensional type and it is additionally viewed as a food source ‘F’ is present in the pursuit space as the target of the swarm. The SSA begins the calculation, approximating the overall optimum by commence a number of salp with irregular positions. Then it evaluates the fitness of every salp and find out the salp location with best fitness, allocate this location to the variable F as food source to be hunt by the chain of salp. For every dimension the position of leader salp is updated and also follower salp position is updated. If any one goes beyond the search space then it will be bring back to the limit. This shows that salp chain can be modelled to pursue a moving food source. Therefore salp chain can be able to have the overall optimum that changes during the iterations.

6. Simulation and Experimental Results
Simulation of the presented model is done by using MATLAB-SIMULINK software version R2018a. In the simulation, doubly-fed induction generator can subjected to speed variation to examine the algorithm. The doubly-fed induction generator parameter value used in the simulation is given in a table. Simulation results of the system is presented in the below sections. In the simulation we can observe the internal determined variables for a better knowledge about the operation of the algorithm. The DFIG model organized for simulation is shown below figure 11.
During the simulation of this model the reference speed is set to 1600 rpm at 2sec, where total simulation time is 10 sec.

From the above figure it can be seen that the rotor speed of the machine changes according to the reference speed given in the inverter control system. The above response curve of speed obtained after optimizing the controllers of the model by using ALO optimizing algorithm. Also the controller are optimised using another algorithm named SSA and the result based on both algorithm are compared in fig 13. in the next page. From the figure shown below it can be seen that the dynamic behaviour of machine is improved when controller are optimised using salp swarm optimisation algorithm.

The developed electromagnetic torque of the machine also follows the reference torque given. The response of electromagnetic torque with respect to the reference torque is shown in the fig 14.
Figure 14. Torque Response curve

The DC link voltage is shown in fig 15. The shown dc link voltage is in per unit. As it can be seen that the dc link voltage is maintained at a constant value throughout the whole simulation.

Figure 15. DC link voltage

The waveform for machine stator voltage and current, also the waveform of rotor current during the simulation of the system is given below figure 16.

Figure 16. Supply Voltage

Figure 17. Stator Current

7. Conclusion
In this report a reliable sensorless control method has been discussed for the doubly-fed induction machine with variable speed. The presented sensorless control technique depends on the MRAS observer which uses reactive power to estimate the speed of the machine. In the talked about observer instantaneous reactive power is utilized by the reference model and steady state reactive power is used by adjustable model. As steady state reactive power are in use in observer operation, the speed estimation method is less sensitive to noise because there is no derivative term in the steady state power. The presented speed estimation technique does not depend on any flux evaluation of either stator of rotor and also it shows less sensitiveness to the resistance variation of both stator and rotor. During sensorless control of stand-alone operated doubly-fed machine by using other MRAS like rotor current based and stator flux based the observer is not able to catch the speed at the time of voltage build up in dc link. The MRAS observer based with reactive power is perfect for speed catching operation.

8. References

[1] J.B. Ekanayake, L. Holdsworth, X.G. Wu, N. Jenkins “Dynamic modelling of doubly-fed induction generator wind turbines,” IEEE Trans. P.S. vol 18 no 2 may 2003.
[2] F. Mei, B.C. Pal, “modelling of doubly-fed induction generator for power system stability study” 2008 IEEE Power and Energy Society General MeetingConversion and Delivery of Electrical Energy in the 21st Century (pp. 1-8).
[3] R. Pena, R. Cardenas, J. Proboste, G. Asher, and J. Clare “Sensorless control of doubly-fed induction generators using a rotor-current based MRAS observer,” IEEE Trans. Ind. Electron, vol 55, no.1, Jan.2008.
[4] L. Morel, H. Godfroid, A. Mirzaian, and J. M. Kauffmann, “Double-fed induction machine: converter optimization and field oriented control without position sensor,” Proc. Inst. Elect. Eng., Electr, Power Appl., vol.145,no.4,pp.360-368,Jul.1998
[5] B. Hopfensperger, D. J. Atkinson, and R. A. Lakin, “Stator-flux oriented control of a doubly-fed induction machine without position encoder,” Proc. Inst. Elect. Eng., Electr, Power Appl., vol. 147, no.4, pp.241-250, Jul. 2000.
[6] R. Datta and V.T. Ranganathan, “ A simple position sensorless algorithm for rotor side field oriented control of wound rotor induction machine,” Ph.D. dissertation, Dept Elect.Eng.,Indian Inst. Science,Bangalore,India,Feb.2000.
[7] L. Xu and W. Cheng, “Torque and reactive power control of a doubly-fed induction machine by position sensorless scheme.” IEEE Trans. Ind. Appl., vol.31, no.3, pp.636-642, May/Jun.1995.
[8] Pattnaik, M. and Kastha, D., 2010, July. Reactive power based MRAS observer for speed sensorless control of double output induction generator. In 2010 5th International Conference on Industrial and Information Systems (pp. 556-561)
[9] E. Bogalecka and Z. Krzeminski, “Sensorless control of a double-fed machine for wind power generators,” in Proc. Eur. Power Electron. Conf-Power Electron., Machines Control, Dubrovnik and Cavtat, Slovenia, 2002.
[10] Ganthia, B.P., Barik, S.K. (2020), Steady-State and Dynamic Comparative Analysis of PI and Fuzzy Logic Controller in Stator Voltage Oriented Controlled DFIG Fed Wind Energy Conversion System. J. Inst. Eng. India Ser. B 101, 273–286. https://doi.org/10.1007/s40031-020-00455-8.
[11] Ganthia, B. P., Barik, S. K., Nayak, B., (2020), “Shunt Connected FACTS Devices for LVRT Capability Enhancement in WECS”, Engineering, Technology &amp; Applied Science Research, 10(3), pp. 5819-5823.
[12] Bibhu Prasad Ganthia, (2019) “Application of Hybrid Facts Devices in DFIG Based Wind Energy System for LVRT Capability Enhancements”. Journal of Mechanics of Continua and Mathematical Sciences. 15. 10.26782/jmcm.2020.06.00019.

[13] B. P. Ganthia, S. Mohanty, P. K. Rana and P. K. Sahu, (2016) "Compensation of voltage sag using DVR with PI controller," International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), Chennai, 2016, pp. 2138-2142, doi: 10.1109/ICEEOT.2016.7755068.

[14] B.P. Ganthia, P.K. Rana, T. Patra, R. Pradhan and R. Sahu, (2018) "Design and Analysis of Gravitational Search Algorithm Based TCSC Controller in Power System", Materials Today: Proceedings, vol. 5, no. 1, pp. 841-847.

[15] Ganthia B.P., Barik S.K., Nayak B. (2021) Wind Turbines in Energy Conversion System: Types & Techniques. In: Singh V.K., Bhoi A.K., Saxena A., Zobaa A.F., Biswal S. (eds) Renewable Energy and Future Power Systems. Energy Systems in Electrical Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-33-6753-1_9

[16] Ganthia, B. P., Barik, S. K., Nayak, B., (2021) “Hardware in Loop (THIL 402) Validated Type-I Fuzzy Logic Control of Type-III Wind Turbine System under Transients”. J. Electrical Systems, 17-1, 28-51. journal/esrgroups.org/jes

[17] B. P. Ganthia, V. Agarwal, K. Rout and M. K. Pardhe, (2017) "Optimal control study in DFIG based wind energy conversion system using PI & GA," 2017 International Conference on Power and Embedded Drive Control (ICPEDC), Chennai, pp. 343-347.

[18] B. P. Ganthia, S. Mohanty, P. K. Rana and P. K. Sahu, (2016) "Compensation of voltage sag using DVR with PI controller," International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), Chennai, 2016, pp. 2138-2142, doi: 10.1109/ICEEOT.2016.7755068.

[19] Pragati A., Ganthia B.P., Panigrahi B.P. (2021) Genetic Algorithm Optimized Direct Torque Control of Mathematically Modeled Induction Motor Drive Using PI and Sliding Mode Controller. In: Kumar J., Jena P. (eds) Recent Advances in Power Electronics and Drives. Lecture Notes in Electrical Engineering, vol 707. Springer, Singapore. https://doi.org/10.1007/978-981-15-8586-9_32

[20] Ganthia B.P., Pradhan R., Sahu R., Pati A.K. (2021) Artificial Ant Colony Optimized Direct Torque Control of Mathematically Modeled Induction Motor Drive Using PI and Sliding Mode Controller. In: Kumar J., Jena P. (eds) Recent Advances in Power Electronics and Drives. Lecture Notes in Electrical Engineering, vol 707. Springer, Singapore. https://doi.org/10.1007/978-981-15-8586-9_35

[21] Subash Ranjan Kabat, Chinmoy Kumar Panigrahi, Bibhu Prasad Ganthia, (2021) Fuzzy Logic Based Fault Current Prediction in Double Fed Induction Generator Based Wind Turbine System, Materials Today: Proceedings, 2021, ISSN 2214-7853, https://doi.org.org/10.1016/j.matpr.2021.06.403.

[22] Satpathy S.R., Pradhan S., Pradhan R., Sahu R., Biswal A.P., Ganthia B.P. (2021) Direct Torque Control of Mathematically Modeled Induction Motor Drive Using PI-Type-I Fuzzy Logic Controller and Sliding Mode Controller. In: Udgata S.K., Sethi S., Srirama S.N. (eds) Intelligent Systems. Lecture Notes in Networks and Systems, vol 185. Springer, Singapore. https://doi.org/10.1007/978-981-33-6081-5_2.

[23] Ganthia, Bibhu Prasad and Subrat Kumar Barik, and Byamakesh Nayak. (2022) "Comparative Analysis of Various Types of Control Techniques for Wind Energy Conversion System." In Modeling and Control of Static Converters for Hybrid Storage Systems. edited by
[24] Ganthia, Bibhu Prasad and Monalisa Mohanty, and Jai Kumar Maherchandani. (2022) "Power Analysis Using Various Types of Wind Turbines." In *Modeling and Control of Static Converters for Hybrid Storage Systems*. edited by Fekik, Arezki, and Nacereddine Benamrouche, 271-286. Hershey, PA: IGI Global. http://doi:10.4018/978-1-7998-7447-8.ch010.

[25] B.P. Ganthia, K. Rout, (2016) Deregulated power system based study of agc using pid and fuzzy logic controller Int. J. of Adv. Res. 4, 847–855. www.journalijar.co.

[26] Ganthia, B.P., Barik, S.K. (2021) Fault Analysis of PI and Fuzzy-Logic-Controlled DFIG-based Grid-Connected Wind Energy Conversion System. *J. Inst. Eng. India Ser. B*. https://doi.org/10.1007/s40031-021-00664-9.

[27] E. Bogalecka, “Power control of a double fed induction generator without speed or position sensor,” in Conf. Rec. EPE,1993, pt. 8,vol.377, ch.50, pp. 224-228.