# Model-based Loss Minimization of a Squirrel Cage Induction Motor with Shorted Rotor Under Indirect Field Orientation

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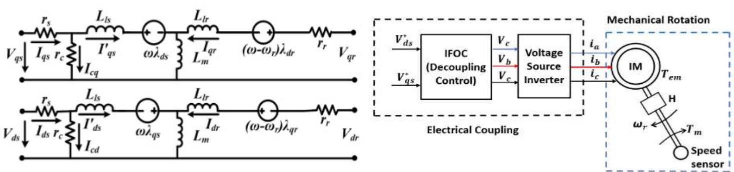
## Introduction and Motivation

1) The ubiquitousness of the induction motor (IM) drives in the domestic, commercial and industrial applications.
2) IM drives are responsible for over 60% of the energy consumed in the industry [1].
3) Vector and PI controllers are the defacto techniques for the control of IM drives in the industries.
4) The need for energy savings, cost reduction and performance improvement in the design of IM drives.
5) Overcoming the challenge of accurately tuning the PI controller to obtain optimal gain values and reducing parameter sensitivity. Genetic Algorithm (GA) is used for the optimal tuning of the gains.
6) Avoiding the use of multiple sensors which can drive up the cost of the IM drives by the application of indirect flux orientation.
7) Reducing computational burden and cost via the use of the simple Jacobian matrix for the optimization instead of the heuristic or numerical optimization techniques

## Model Development of the Shorted Rotor Induction Motor




From the d-q model circuit model [2] and the electromechanical coupling diagram above, we develop the dynamics of the IM drive as:

$$\begin{bmatrix} \frac{d\lambda_{ds}}{dt}\\ \frac{d\lambda_{qs}}{dt}\\ \frac{d\lambda_{dr}}{dt}\\ \frac{d\lambda_{qr}}{dt}\end{bmatrix} = \begin{bmatrix}0&\omega&0&0\\-\omega&0&0&0\\0&\omega_{so}&0&0\\-\omega_{so}&0&0&0\end{bmatrix}\begin{bmatrix}\lambda_{ds}\\ \lambda_{qs}\\ \lambda_{dr}\\ \lambda_{qr}\end{bmatrix} + \begin{bmatrix}r_s&0&0&0\\0&r_s&0&0\\0&0&r_r&0\\0&0&0&r_r\end{bmatrix}\begin{bmatrix}I_{ds}\\ I_{qs}\\ I_{dr}\\ I_{qr}\end{bmatrix} + \begin{bmatrix}V_{ds}\\ V_{qs}\\ 0\\ 0\end{bmatrix}$$

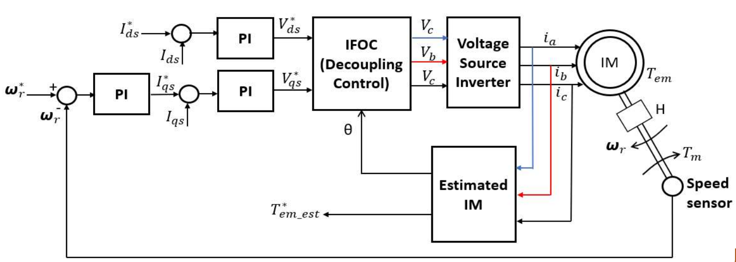
$$\frac{d\omega_r}{dt} = \frac{p}{2H}(T_{em} - T_m)$$

$$T_{em} = \frac{3pL_m}{4}(I_{dqs} \times I_{dqr}) = \frac{3pL_m}{4}(I_{dqs}^T J\, I_{dqr})$$

$$\text{where } I_{dqs} = \begin{bmatrix}I_{ds}\\ I_{qs}\end{bmatrix}, I_{dqr} = \begin{bmatrix}I_{dr}\\ I_{qr}\end{bmatrix}, \text{and } J = \begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}$$

## Methodology

**IFOC:** Assuming negligible switching and conduction losses from the PWM inverter [3], the IFOC PI control diagram is shown below:




$$\lambda_{qr} = 0, \dot{\lambda}_{qr} = 0, \quad \lambda_r = \lambda_{dr}$$

$$\lambda_{dr} = \lambda_r = \frac{L_m I_{ds}}{1 + s\tau_r}$$

$$(\omega - \omega_r) = \frac{r_r L_m}{L_r}\frac{I_{qs}}{\lambda_{dr}}$$

where $\tau_r = \frac{L_r}{r_r}$ is the rotor time constant

$$P_L = \frac{3}{2}I_r^2\left(\alpha + \frac{\beta\omega}{(\omega - \omega_r)} + \frac{\gamma}{(\omega - \omega_r)^2}\right)$$

$$T_{em} = T_m = \frac{3pr_r}{4(\omega - \omega_r)}I_r^2$$

$$\begin{vmatrix}\frac{\partial P_L}{\partial \omega} & \frac{\partial P_L}{\partial I_r}\\ \frac{\partial T_m}{\partial \omega} & \frac{\partial T_m}{\partial I_r}\end{vmatrix} = 0$$

$$\omega_{\text{opt}} - \omega_r = \pm\sqrt{\frac{\gamma}{\alpha + \beta}}$$

$$|\lambda_{r_{\text{opt}}}| = \sqrt{\frac{4r_r T_m}{3p}\sqrt{\frac{\alpha+\beta}{\gamma}}}$$

Then the required current references , the control error are computed as:

$$I_{ds}^* = \frac{|\lambda_{r_{opt}}|}{L_m}$$

$$I_{qs}^* = \frac{4T_{em}L_r}{3pL_m\lambda_r}$$

$$I_{ds}^* - I_{ds} = I_{qs}^* - I_{qs} = e$$

The PI controllers are modelled as follows:

$$I_{ds} = I_{ds}^* - K_p V_{ds}^* - K_i\int_0^t V_{ds}^*(\tau)\, d\tau$$

$$I_{qs} = I_{qs}^* - K_p V_{qs}^* - K_i\int_0^t V_{qs}^*(\tau)\, d\tau$$

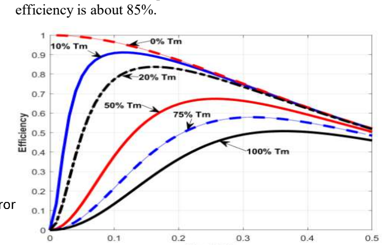
$$\omega_r = \omega_r^* - K_p I_{qs}^* - K_i\int_0^t I_{qs}^*(\tau)\, d\tau$$

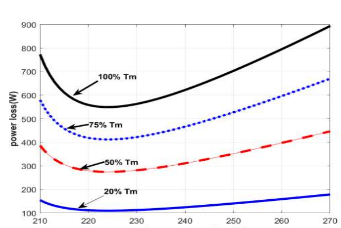
At steady state, The power loss and efficiency equations are derived as:

$$P_L = \frac{3}{2}I_r^2\left(\alpha + \frac{\beta\omega}{(\omega - \omega_r)} + \frac{\gamma}{(\omega - \omega_r)^2}\right)$$

$$\eta = \frac{2400\lambda_r^2}{2400\lambda_r^2 + \zeta\lambda_r^4 + \mu T_m^2}$$

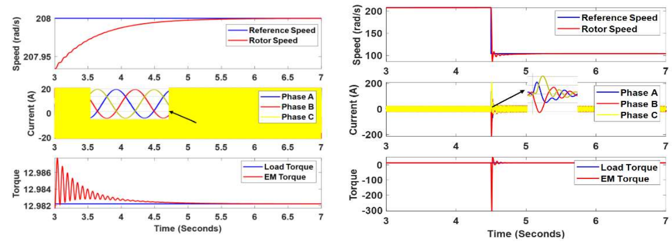
- The following results are plotted from the two equations above.
- The optimal speed is 225 rad/s and the corresponding optimal flux is 0.323Wb.
- The optimal rotor speed at this point is 208 rad/s. Efficiency is over 90% at a load torque of less than 10%. At 20% load, the efficiency is about 85%.



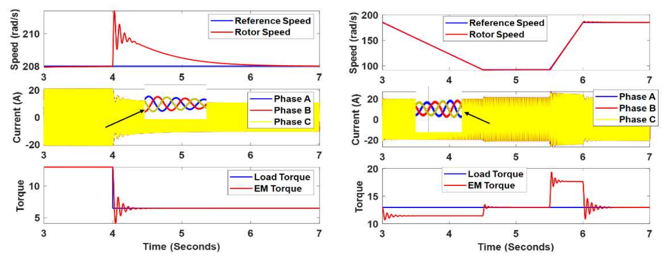




## Results

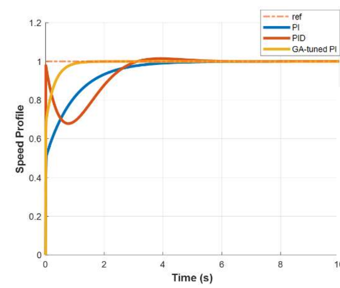
- The rotor speed tracks the reference speed with a very low steady state error. The currents and the generated torque also follows the reference speed and tracks the load torque effectively.
- Similarly, when the reference speed drops to half its initial value at 4secs, the rotor speed, currents and the torque tracks effectively. Although, the torque dips at 4secs and returns to steady state almost immediately with the help of the PI controller.




- The response of the rotor speed and the torque to the change in load is shown below with the speed, currents and torque all tracking the constant speed reference perfectly.
- Also, a drive cycle speed reference response is shown in the next figure, in which the rotor speed, currents and the torque tracks the reference trajectory accurately with minimum chattering.




- Comparative analysis of the proposed Jacobi-PI, genetic algorithm (GA) tuned PI and the PID controllers is presented in the diagram and the table below.
- The GA is used to improve the performance of the PI controller through optimization to extract the optimal gains. Hence, the response shows that GA-PI is the most resilient of the three controllers tested.
- The GA-PI is superior in all metrics except in computational time.




| Method | Jacobi-PI | GA-PI | PID |
|---|---|---|---|
| *Computation* | Fastest | Slower | Faster |
| *Implementation* | Simplest | Complex | Simpler |
| *Torque ripple* | Lower | Lowest | Highest |
| *Overshoot* | 0% | 0% | 3.07% |
| *Settling time* | 6 secs | 1.5 secs | 6 secs |
| *Rise time* | 1.47 secs | 0.31 secs | 2.14 secs |
| *Parameter requirement* | $\tau_r$ | none | $\tau_r$ |
| *Parameter Sensitivity* | Yes | None | yes |

## Conclusion and Future Work

This poster presents a model-based Indirect field orientation control (IFOC) of a shorted rotor induction motor with the aim of lowering the cost and losses in the drive.

1) The IFOC is used to ensure decoupled control of the field-dependent and torque-dependent components of the stator current just like in DC motor drives.
2) The reference torque and speed are computed via the Jacobian Loss minimization technique at steady state.
3) Independent control of the decoupled components of the current and the speed are controlled by PI controllers. GA is applied to select the optimal gains for the controller.
4) The system is tested using the proposed Jacobi-PI, GA-tuned PI and PID with the GA-tuned PI emerging as the most robust and effective of the three.
5) In the future, the performance of the drive will be tested with more robust control algorithms and reference flux and angle will be estimated and optimized via an observer design and more advanced numerical optimization methods with consideration for transient behavior of the system. Experimental testing would also be performed to validate the numerical simulation results.

## Reference


1. J. F. Stumper, A. D¨otlinger, and R. Kennel, “Loss minimization of induction machines in dynamic operation,” IEEE transactions on energy conversion, vol. 28, no. 3, pp. 726–735, 2013.
2. P. C. Krause, O. Wasynczuk, S. D. Sudhoff, and S. D. Pekarek, Analysis of electric machinery and drive systems. John Wiley & Sons, 2013, vol. 75.
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