Dead-time Induced Oscillations in Inverter-fed Induction Motor Drives

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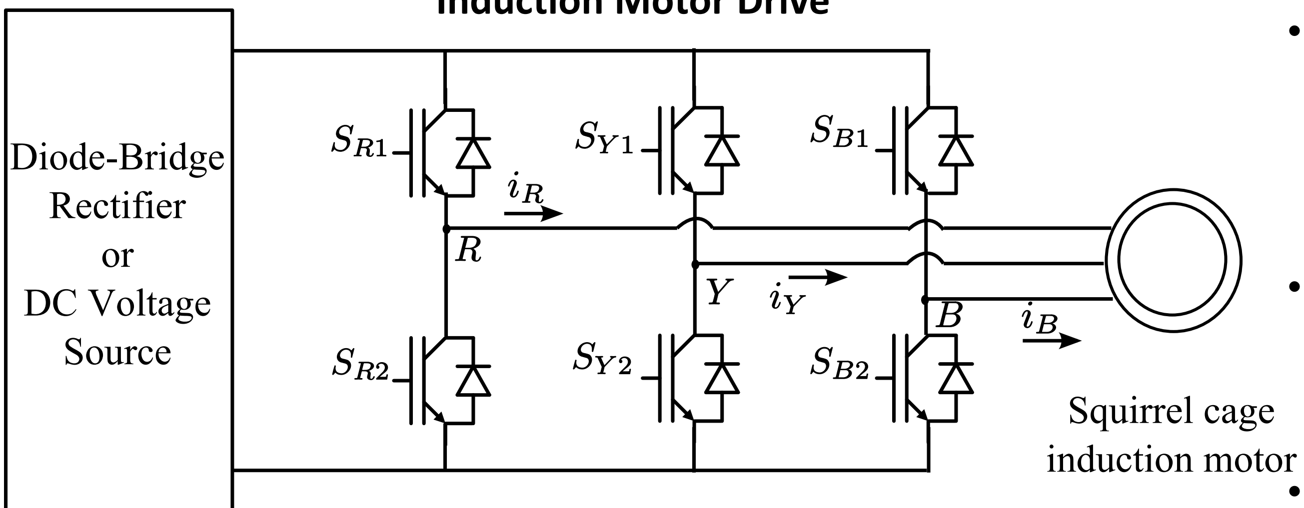
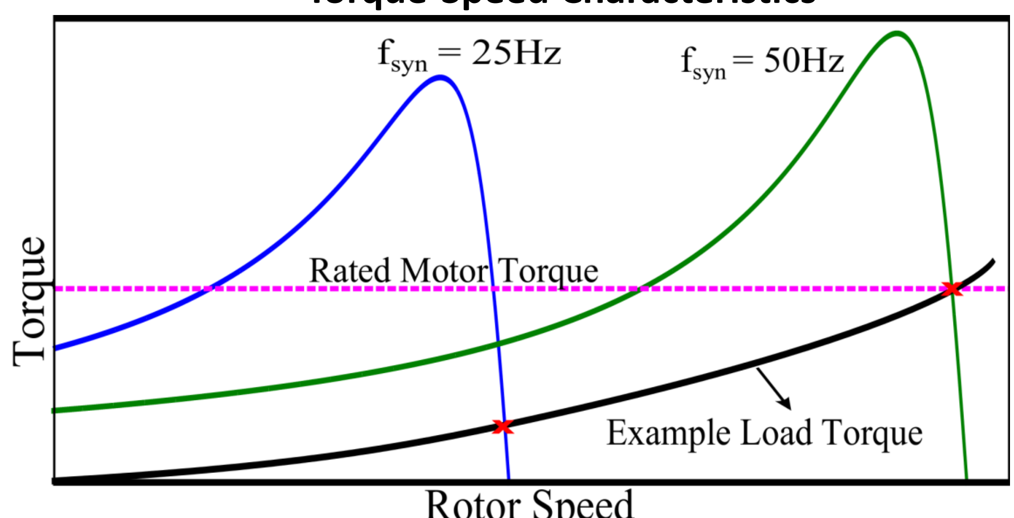
Inverter-fed Induction Motor and V/f Control

Induction Motor Drive



3ϕ two-level voltage source inverter

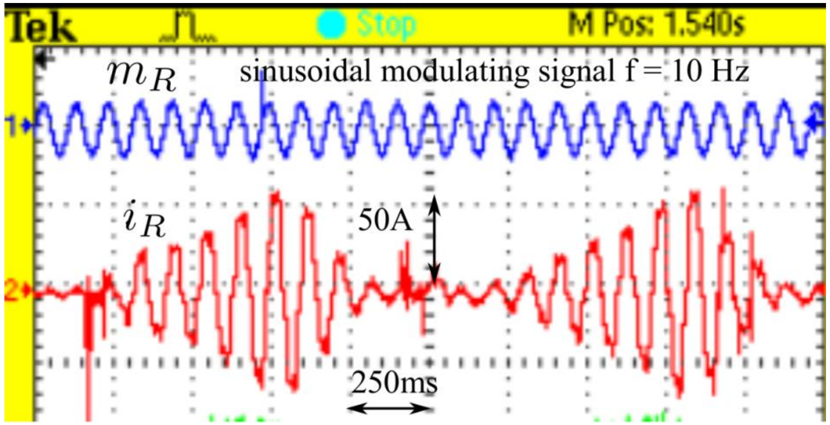
Torque-Speed Characteristics



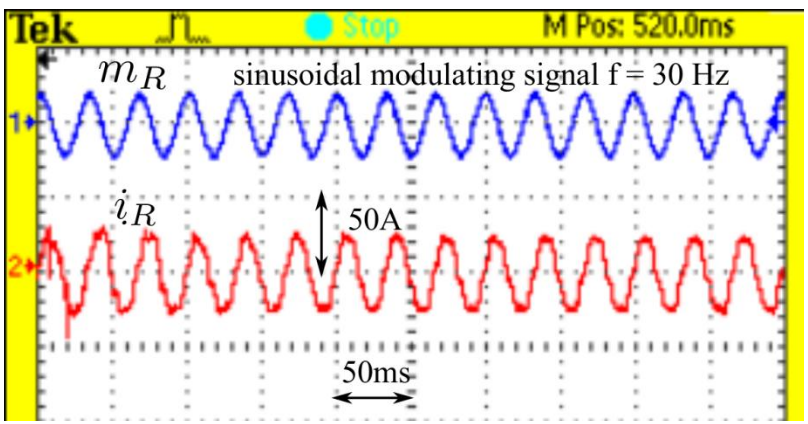
- Inverter- fed induction motor - for variable speed operation.
- Simple control - Constant *V/f* control of induction motors.
- Used for loads such as fans, pumps, compressors etc. These loads operate at light-loads at low speeds.
- Also during initial testing of inverters and induction motors, motor drive is typically run under no-load conditions using *V/f* control.

Dead-time Induced Sub-harmonic Oscillations in a 100-kW Inverter-fed Induction Motor.

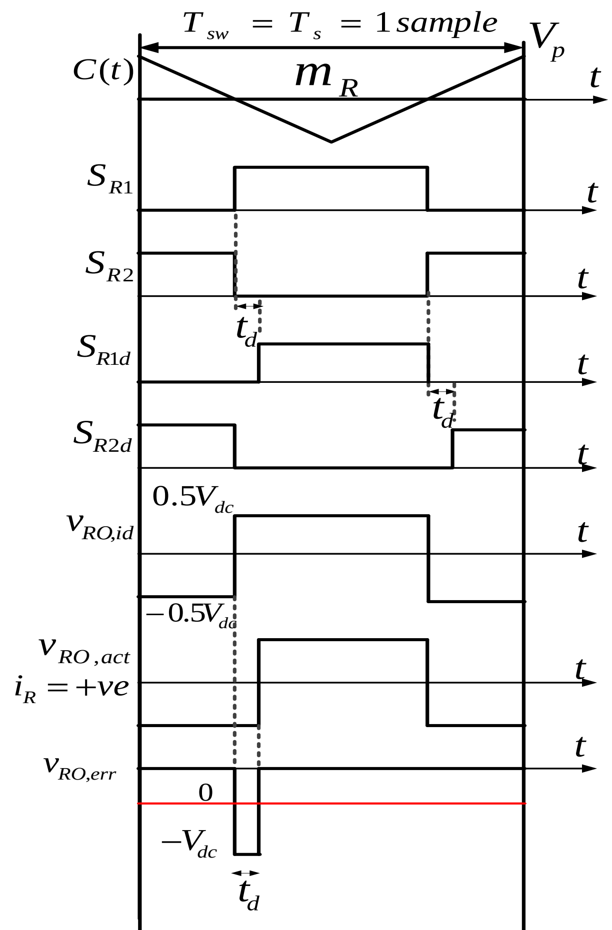
Sustained sub-harmonic oscillations in current at f1 = 10Hz



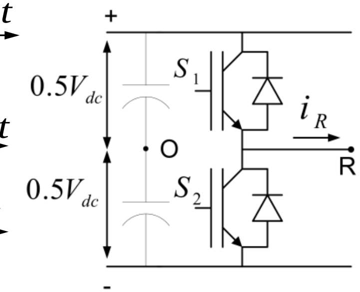
Normal behaviour at f1 = 30Hz



Dead-time effect



Inverter leg



- Oscillatory behaviour of the drive at low and medium speeds, particularly under no-load.
- Inverter dead-time results in /accentuates the oscillatory behaviour of the drive.
- Model drive including dead-time effect to predict where oscillations occur.

Modeling of Induction Motor Drive Including the Effect of Inverter Dead-time

- Dead-time effect alters the stator voltage equations of the motor drive.

$$v_{qs,id} = \left(r_s + L_s \frac{d}{dt} + \boxed{\frac{|\overrightarrow{V}_{s,err,f}|}{\sqrt{i_{qs}^2 + i_{ds}^2}}} \right) i_{qs} + \omega_s L_s i_{ds} + L_m \frac{di'_{qr}}{dt} + \omega_s L_m i'_{dr}$$

$$v_{ds,id} = -\omega_s L_s i_{qs} + \left(r_s + L_s \frac{d}{dt} + \boxed{\frac{|\overrightarrow{V}_{s,err,f}|}{\sqrt{i_{qs}^2 + i_{ds}^2}}} \right) i_{ds} - \omega_s L_m i'_{qr} + L_m \frac{di'_{dr}}{dt}$$

- Non-linearity in stator dynamic equations on account of dead-time effect.

- The effect of dead-time impacts the steady-state operating point of the drive system as well.

- Small-signal model of the drive derived by linearising the non-linear system dynamic equations about a steady-state operating point.

Review of Small-signal Model of Inverter fed Induction Motor Including Inverter Dead-time

$$\mathbf{\Delta x} = [\Delta i_{qs} \;\; \Delta i_{ds} \;\; \Delta i'_{qr} \;\; \Delta i'_{dr} \;\; \Delta \omega_r]^T$$

$$\mathbf{\Delta \dot{x}} = \mathbf{A} \; \mathbf{\Delta x} + \mathbf{B} \; \mathbf{\Delta u}$$

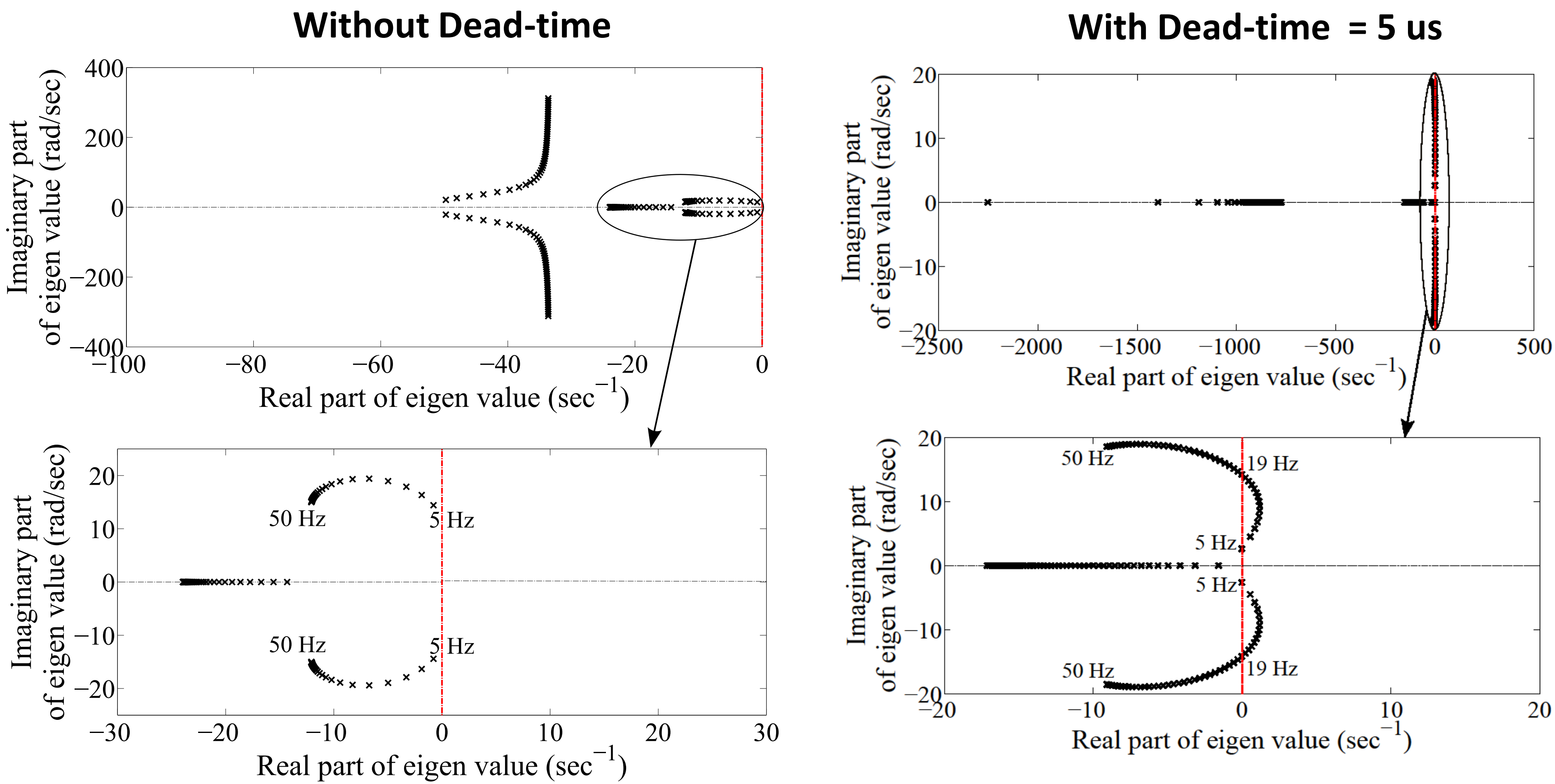
$$\mathbf{A} = \begin{bmatrix} -\mathbf{L}^{-1}\mathbf{R} & -\mathbf{L}^{-1}\lambda_{10} \\ \left(\frac{3}{2J}\right)\left(\frac{poles}{2}\right)^2 \lambda_{20}^{\mathbf{T}} & -\frac{B}{J} \end{bmatrix}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{R_{ss}} & \mathbf{R_{sr}} \\ \mathbf{R_{rs}} & \mathbf{R_{rr}} \end{bmatrix}$$

$$\mathbf{R_{ss,prop}} = \begin{bmatrix} r_s + \boxed{R_{q,eq0}} & \omega_{s0} L_s - \boxed{X_{qd,eq0}} \\ -(\omega_{s0} L_s + \boxed{X_{qd,eq0}}) & r_s + \boxed{R_{d,eq0}} \end{bmatrix}$$

- Impact of inverter dead-time is observed in the stator R_{ss} submatrix.
- Details of the 5^{th} order model in the poster.
- Stability analysis performed with the small-signal model.

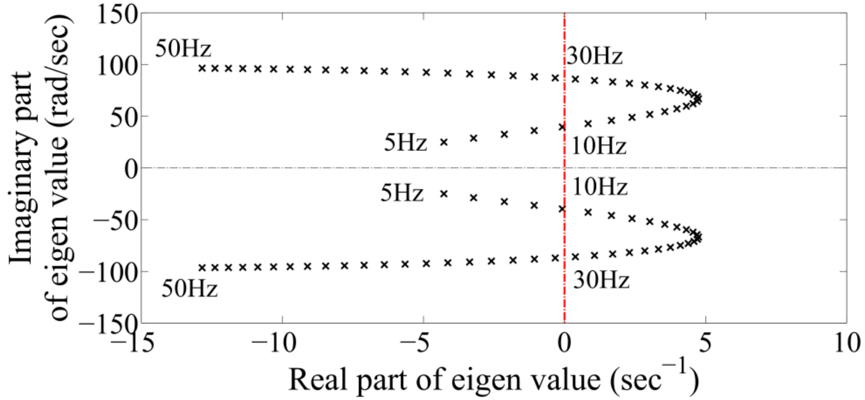
Locus of Eigen Values of the 100kW Motor Drive – Without and With Dead-Time



- Without dead-time: eigen values with only negative real parts – no oscillatory behaviour expected.
- With dead-time: oscillations expected between 5 Hz and around 19 Hz – explains expt. observations
- Conditions: V_{dc} = 590 V, f_{sw} = 5 kHz, V/f =0.61 pu (reduced flux)

Region of Oscillatory Behaviour of a 11kW Induction Motor Drive on the Voltage-frequency plane

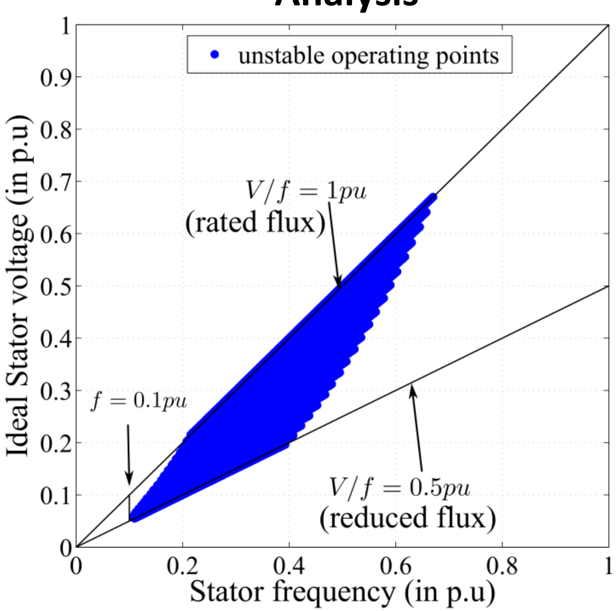
Root loci with dead-time



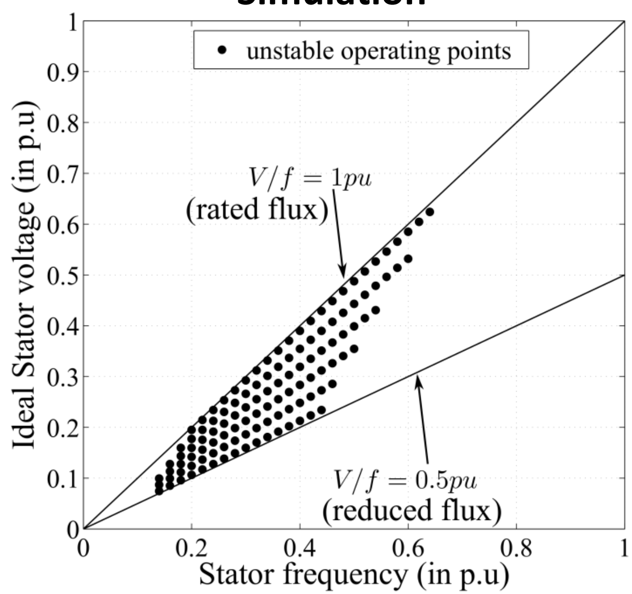
- Eigen values plotted for t_d = 3us, f_{sw} = 5kHz, V_{dc} = 600V, V/f = 0.89 pu.
- Region of oscillatory behaviour obtained considering different V/f ratios or flux levels.
- Measurements of oscillatory behaviour in 11kW induction motor, and in few other motors of different power levels carried out in collaboration with an industry.

Region of Oscillatory Behaviour:

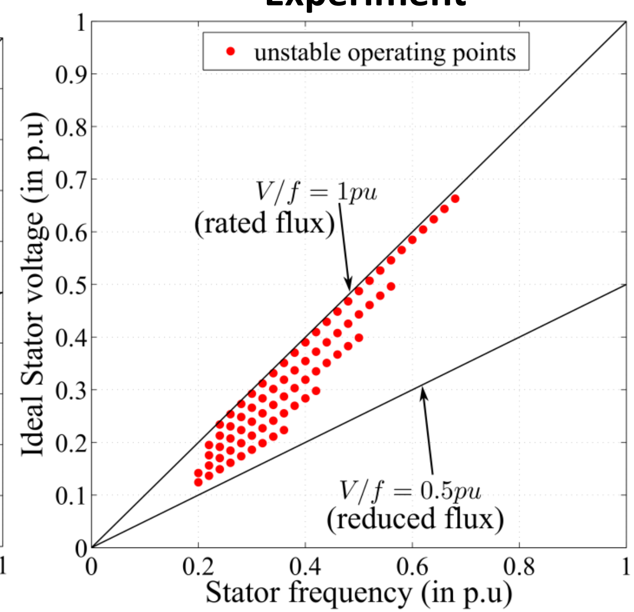
Analysis



Simulation

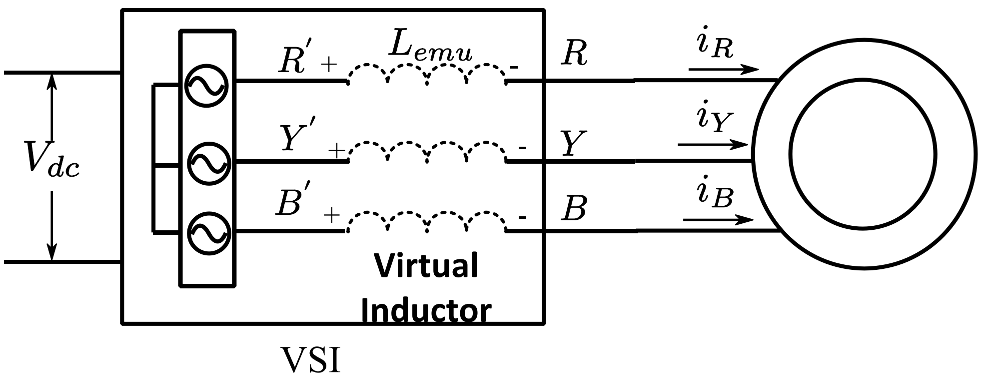


Experiment

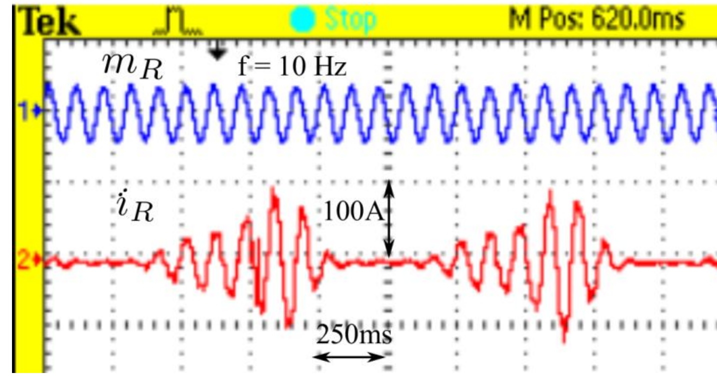


Mitigation of Small-signal Instability : Emulation of a Virtual Series Inductor

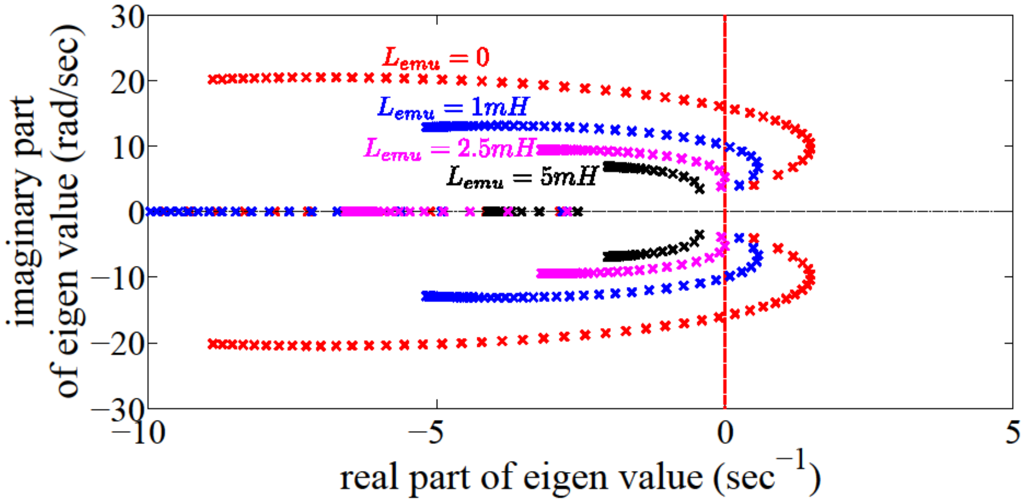
Inductance Emulation Concept



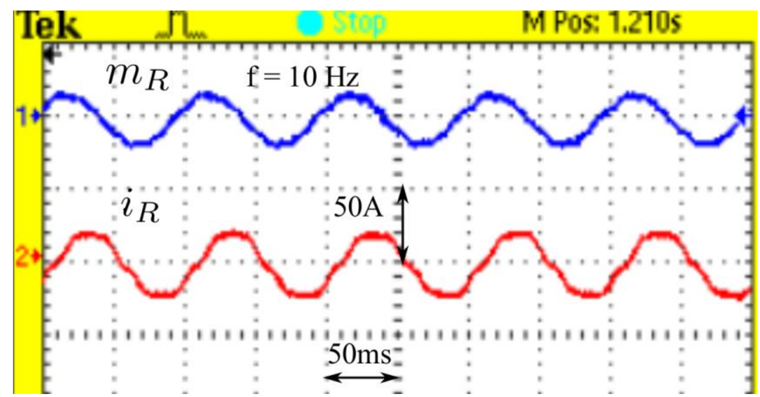
Simple V/f control



Eigen values with series inductance



Proposed control with inductance emulation



- Inverter is controlled such that the terminal voltage is the sum of the ideal sinusoidal voltage (corresponding to the ideal modulating signal) and the voltage drop across the series inductor.

Conclusions and Contributions

1. Oscillatory behaviour measured in induction motor drives of different power levels – Collaboration with industry for some of these measurements.

2. a) Dynamic model of inverter-fed induction motor including effect of dead-time.
   b) Steady-state solution of inverter-fed induction motor including dead-time.

3. a) Small-signal model of inverter-fed induction motor including dead-time.
   b) Stability analysis to predict region of oscillatory behaviour – experimental validation on 100kW and 11kW motors.

4. Active damping method based on inductance emulation to mitigate dead-time induced oscillations.

5. Improved dynamic model of rectifier-inverter fed induction motor – including impact of dead-time on inverter dc input current and dc link dynamics.

6. Under-compensation and over-compensation of dead-time effect - Demonstration of two types of oscillatory behavior in the drive

Key Publications:

[1] A. Guha and G. Narayanan, "Small-signal stability analysis of an open-loop induction motor drive including the effect of inverter dead-time," in IEEE Trans Ind. Appl., vol 52, no1, pp 242-253, 2016

[2] A. Guha and G. Narayanan, "Modelling and analysis of induction motor drive including the effect of inverter dead-time," Sadhana, March 2016.

[3] A. Guha and G. Narayanan, "Inductance-Emulation-Based Active Damping of Dead-Time-Induced Oscillations in a 100-kW Induction Motor Drive" in Proc. IEEE Transportation and Electrification Conf., ITEC – India, Aug 2015.

[4] A. Guha, C. Abhishek, C. Kumaresan, G. Narayanan, and R. Krishnamoorthy, "Theoretical prediction and experimental verification of light-load instability in a 11-kw open-loop induction motor drive," in Proc. NPEC 2015, Bombay, India

[5] A. Guha and G. Narayanan , " Impact of Dead-time on Inverter Input Current, DC-link Dynamics and Light-load Instability in Rectifier-Inverter-fed Induction Motor Drives, accepted in IEEE SPEEDAM, Italy 2016.

[6] A. Guha, A. Tripathi, and G. Narayanan, "Experimental study on dead-time induced oscillations in a 100-kw open-loop induction motor drive," in Proc. National Power Electronics Conference NPEC 2013, Kanpur, India.

[7] A. Guha and G. Narayanan, "An Improved Dead-Time Compensation Scheme for Voltage Source Inverters Considering the Device Switching Transition Times," in Proc. IEEE IICPE, 2014, Kurukshetra, India

[8] A. Guha, C. Abhishek, E,Panda, C. Kumaresan, G. Narayanan, and R. Krishnamoorthy, "Experimental Case Studies on Dead-Time Induced Oscillations and its Mitigation in 5-HP and 10-HP Induction Motor Drives", in IEEE ICEES 2016