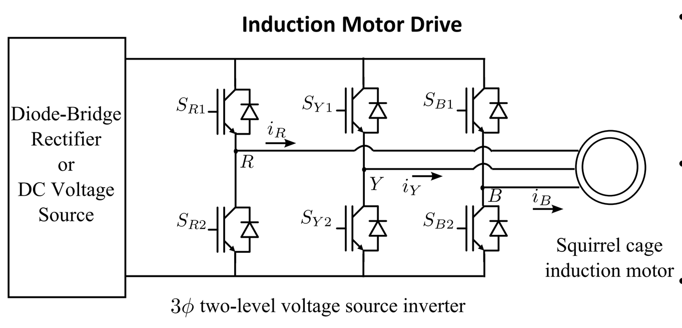
# Dead-Time Induced Oscillations in Inverter-fed Induction Motors

PhD Scholar : Anirudh Guha    Advisor: Prof. G Narayanan

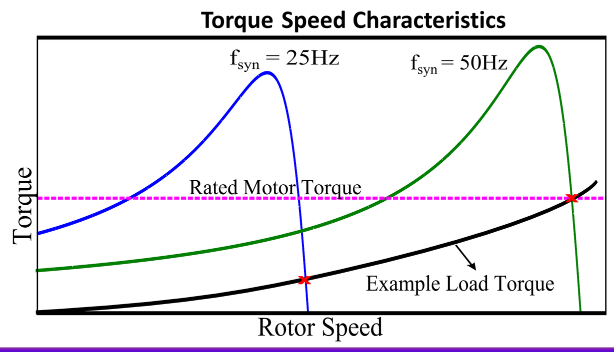
Department of Electrical Engineering, Indian Institute of Science, Bangalore

## Inverter-fed Induction Motor and V/f control

Induction Motor Drive



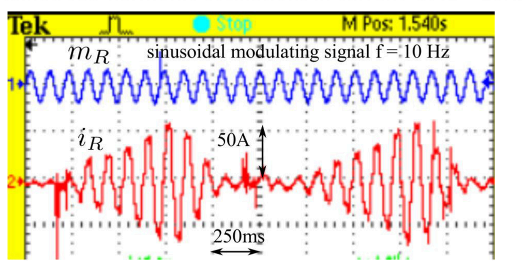

Torque Speed Characteristics



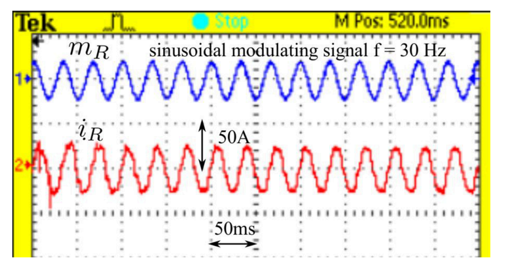

- Inverter- fed induction motor - for variable speed operation.
- Simple control - Constant *V/f* control of induction motors.
- Used for loads such as fans, pumps, compressors etc. These loads operate at light-loads at low speeds.
- Also during initial testing of inverters and induction motors, motor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

## Dead-time Induced Sub-harmonic Oscillations in a 100-kW Inverter-fed Iduction Motor

Sustained sub harmonic oscillations in current at f1 = 10Hz

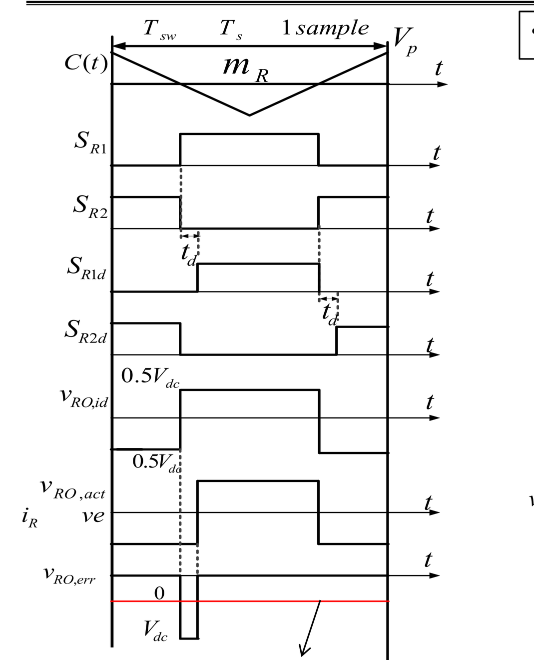


Normal behaviour at f1 = 30Hz



- Oscillatory behaviour of the drive at low and medium speeds, particularly under light-loads.
- Many a times, such oscillations in induction motors are misconstrued to be mechanical problems – shaft alignment, coupling.
- Inverter dead-time results in or accentuates the oscillatory behaviour of the drive.
- Model drive including dead-time effect to predict where oscillations occur.

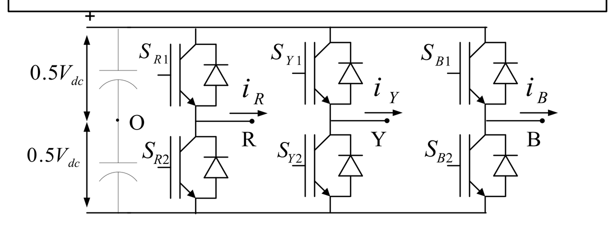
## Inverter Dead-time: Review of Instantaneous and Average Dead-time Error Voltages

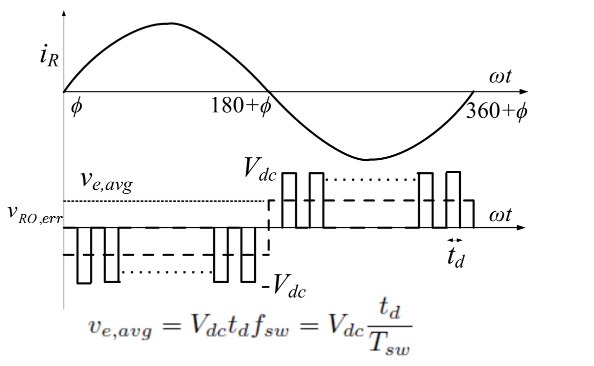


$v_{RO,err,avg} = -V_{dc} t_d f_{sw} sign(i_R)$

Switching-Cycle-Averaged Error Voltage

•Dead-time introduced in gating pulses for safe commutation



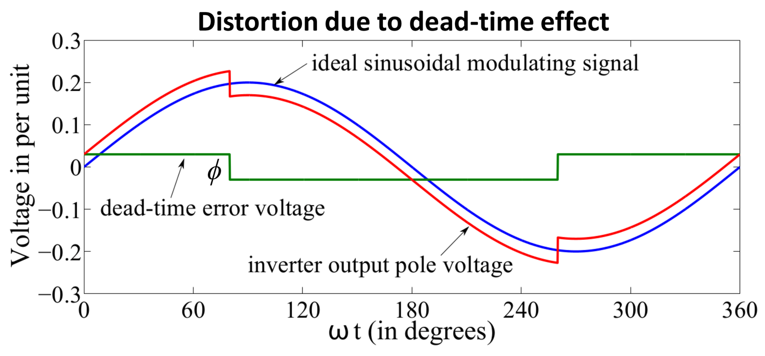


$v_{e,avg} = V_{dc} t_d f_{sw} = V_{dc} \frac{t_d}{T_{sw}}$

•Square-wave error voltage depends on current polarity

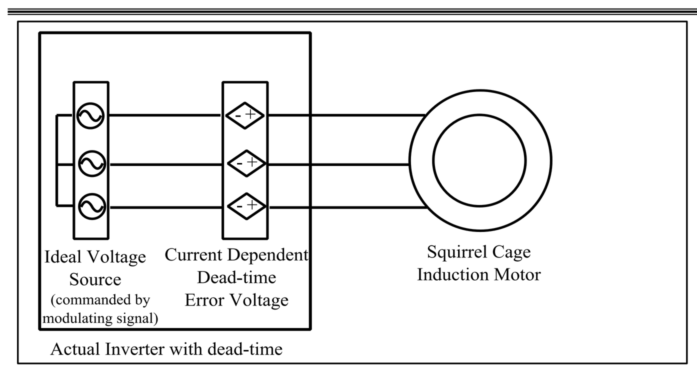
## Actual Inverter Output Voltage: Distortion due to Dead-time Effect

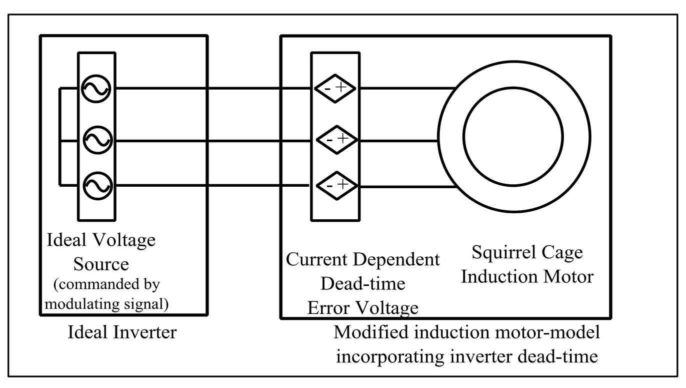
Distortion due to dead-time effect




- Dead-time effect causes a change in the fundamental output voltage and also results in harmonic distortion.

## Schematic Representation of Inverter-fed Induction Motor





- Actual inverter with dead-time feeding an induction motor
- Dead-time error voltage magnitude constant.
- Error voltage phase depends on load current polarity/phase.
- For analysis, dead-time effect is incorporated into the motor model (to see how this could equivalently impact motor impedances).
- For purpose of analysis , only fundamental component of dead-time error voltage is considered.
- Dead-time error voltages are transformed into the synchronous *dq* reference frame, and incorporated with the *dq* model of the motor.

## Dynamic Model of Induction Motor Including the Effect of Dead-Time : Model is seen to be non-linear

Stator voltage equations

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

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

Rotor voltage equations

$$v'_{qr} = 0 = L_m\frac{di_{qs}}{dt} + (\omega_s - \omega_r)L_m i_{ds} + (r'_r + L'_r \frac{d}{dt}) i'_{qr} + (\omega_s-\omega_r)L'_r i'_{dr}$$

$$v'_{dr} = 0 = -(\omega_s-\omega_r)L_m i_{qs} + L_m \frac{di_{ds}}{dt} - (\omega_s-\omega_r)L'_r i'_{qr} + (r'_r + L'_r\frac{d}{dt}) i'_{dr}$$

Mechanical dynamic equation

$$T_l = \frac{3}{2}\left(\frac{poles}{2}\right) L_m (i_{qs} i'_{dr} - i_{ds} i'_{qr}) - \left(\frac{2}{poles}\right) J \frac{d\omega_r}{dt} - \left(\frac{2}{poles}\right) B\omega_r$$

## Proposed Small-signal Model

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

$$\Delta \mathbf{u} = [\Delta v_{qs,id}\ \ \Delta v_{ds,id}\ \ 0\ \ 0\ \ \Delta T_l]^T$$

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

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

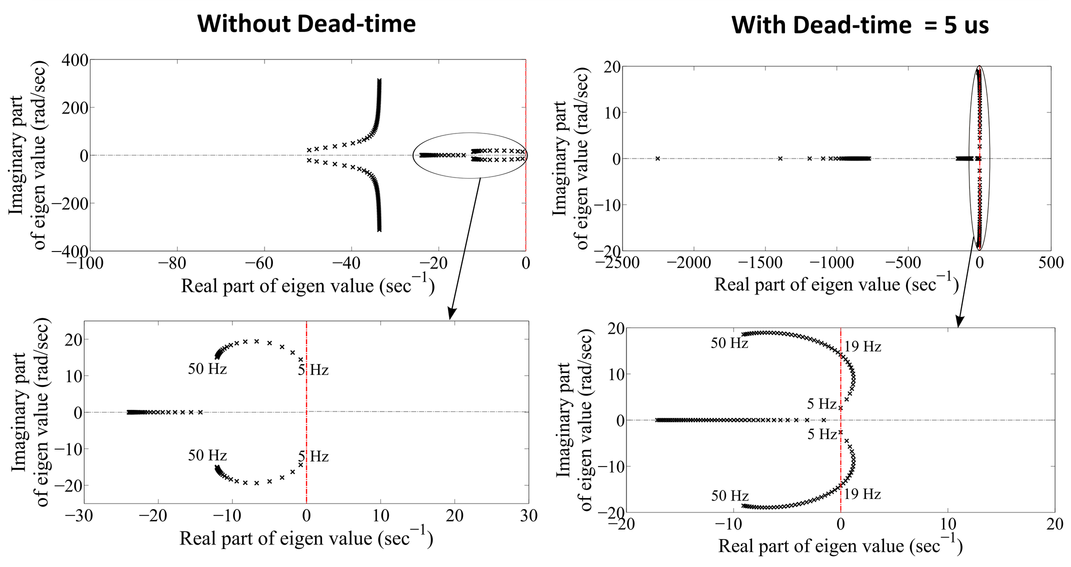
$$\mathbf{R} = \begin{bmatrix} \mathbf{R_{ss}} & \mathbf{R_{sr}} \\ \mathbf{R_{rs}} & \mathbf{R_{rr}} \end{bmatrix} \qquad \mathbf{R_{ss,prop}} = \begin{bmatrix} r_s + R_{q,eq0} & \omega_{s0}L_s - X_{qd,eq0} \\ -(\omega_{s0}L_s + X_{qd,eq0}) & r_s + R_{d,eq0} \end{bmatrix}$$

$$R_{q,eq0} = R_{eq0}\left(\frac{i_{ds0}^2}{i_{qs0}^2+i_{ds0}^2}\right) \qquad R_{d,eq0} = R_{eq0}\left(\frac{i_{qs0}^2}{i_{qs0}^2+i_{ds0}^2}\right)$$

$$X_{qd,eq0} = R_{eq0}\left(\frac{i_{qs0}i_{ds0}}{i_{qs0}^2+i_{ds0}^2}\right) \qquad R_{eq0} = \frac{|\vec{V}_{s,err,f}|}{\sqrt{i_{qs0}^2+i_{ds0}^2}}$$

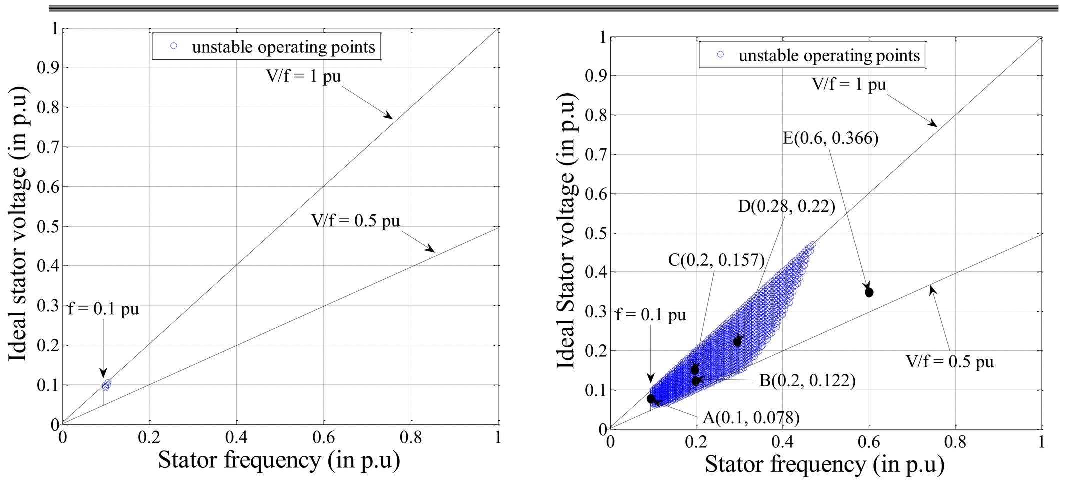
### Locus of Eigen Values of the 100kW Motor Drive – Without and With Dead-Time

Without Dead-time    With Dead-time = 5 us



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

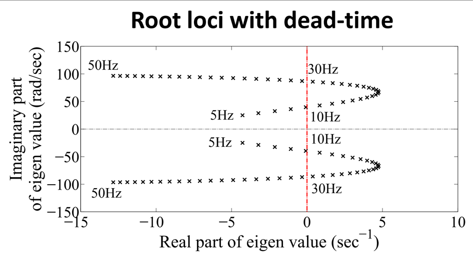
## Region of Oscillatory Behaviour on Voltage-Frequency Plane




without dead-time    with dead-time

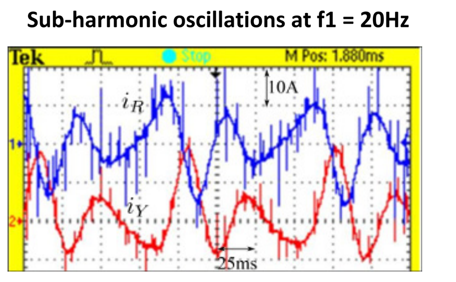
## Region of Oscillatory Behaviour of a 11kW Induction Motor Drive on the Voltage-frequency plane

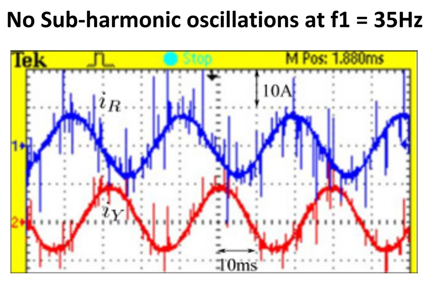
Root loci with dead-time



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

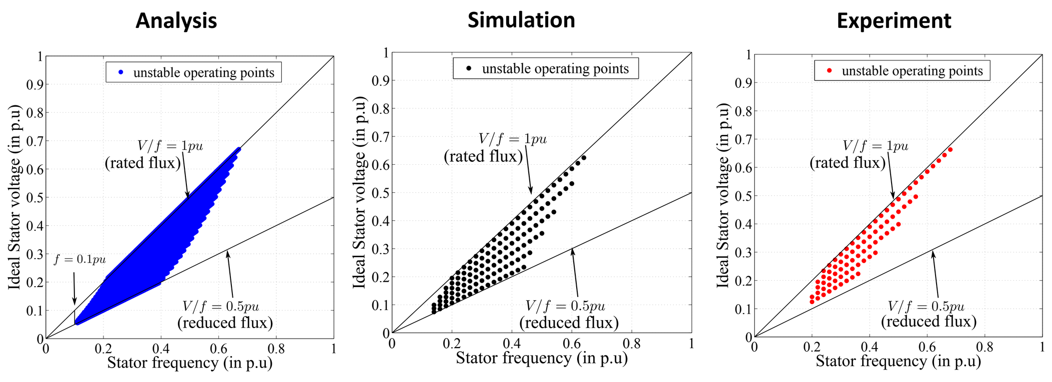
Sub-harmonic oscillations at f1 = 20Hz    No Sub-harmonic oscillations at f1 = 35Hz



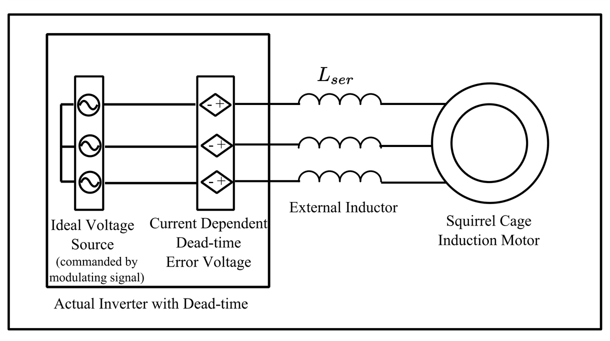


Region of Oscillatory Behaviour

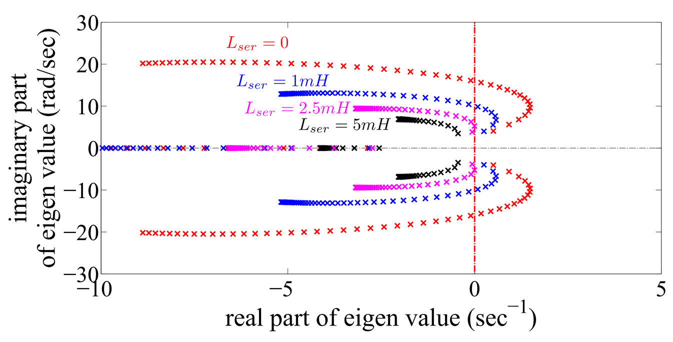
Analysis    Simulation    Experiment



## Mitigation of Small-signal Instability by Connecting an External Series Inductor



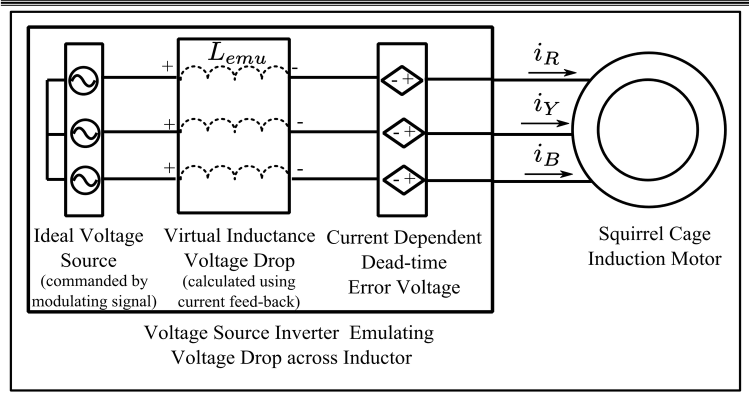
- Schematic representation of an inverter-fed motor with an external series inductance.
- Additional inductance could mitigate oscillatory behaviour.




- Zoomed view of root locus branch close to jw axis.
- Eigen values migrate to the left as the external inductance is increased to 5mH.

Conditions: Vdc = 590V, fsw = 5kHz, V/f = 0.7 pu, td = 5us.

## Virtual Inductance Emulation



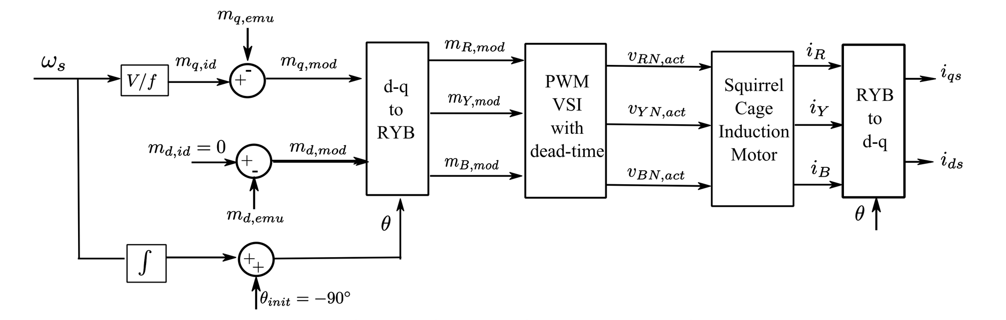

- Inductor voltage to be subtracted from ideal voltage commanded by modulating signal.
- Current feed-back required for calculating inductor voltage drop.
- Inductive voltage drop calculated in *dq* reference frame.

Voltage drop across inductor along q-axis and d-axis :

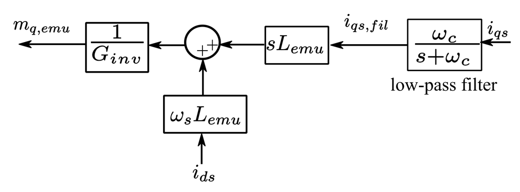
$$v_{qs,ind} = \left(L_{emu}\frac{d}{dt}i_{qs}\right) + \omega_s L_{emu} i_{ds} \qquad v_{ds,ind} = \left(L_{emu}\frac{d}{dt}i_{ds}\right) - \omega_s L_{emu} i_{qs}$$

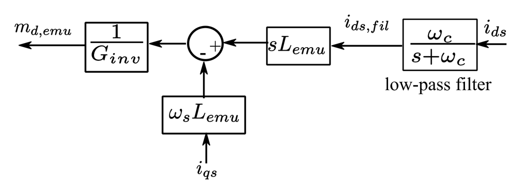
- Low-pass filter required. Cannot implement derivative operation in digital controller directly due to noise in the current feed back.

## Block Diagram of Proposed Control Strategy



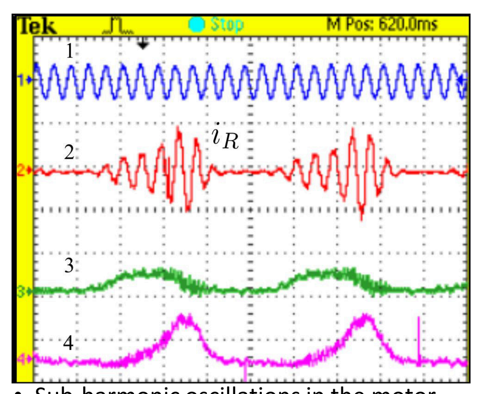
Volts-per-hertz induction motor drive





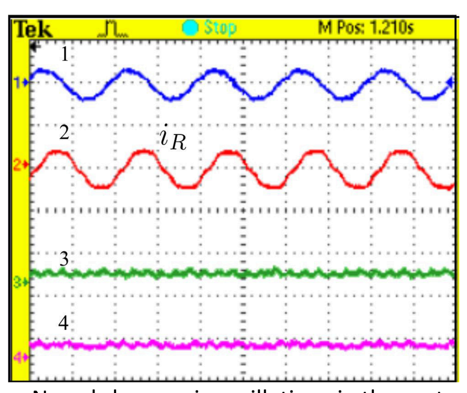
q-axis inductance emulation    d-axis inductance emulation

## Experimental Results: 100-kW Induction Motor Drive Operated at a Fundamental Frequency f1 = 10Hz



- Sub-harmonic oscillations in the motor current with **simple V/f control.**

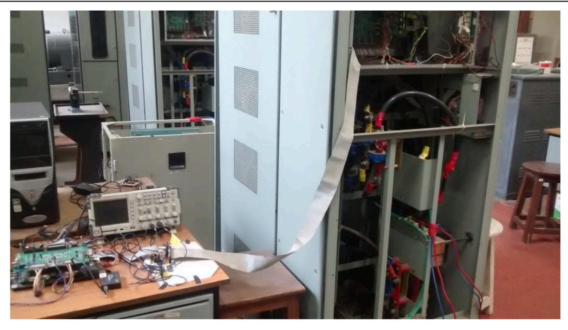
Trace 1: R-phase modulating signal (2V/div),
Trace 2: R-phase current (100A/div),
Trace 3: q-axis current (100A/div),
Trace 4: d-axis current (100A/div),
Horizontal scale: 250 ms/div

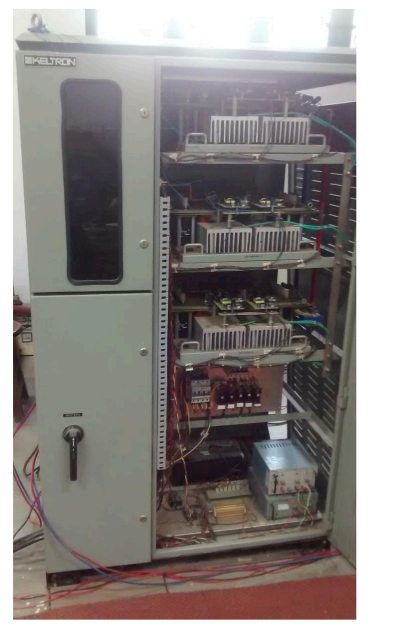


- No sub-harmonic oscillations in the motor current with the **proposed active damping method.**

Trace 1: R-phase modulating signal (2V/div),
Trace 2: R-phase current (50A/div),
Trace 3: q-axis current (50A/div),
Trace 4: d-axis current (50A/div),
Horizontal scale: 50 ms/div

## 100-kW Experimental Setup





## 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 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.

[5] 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 NPEC 2015, Mumbai, India, Dec 2015

[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. NPEC 2013 , Kanpur, India, Dec 2013.