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RE-IMAGINING THE ELECTRIC GRID

Nonintrusive Load Modeling:

Advanced Monitoring & Prognostics for SPIM Loads

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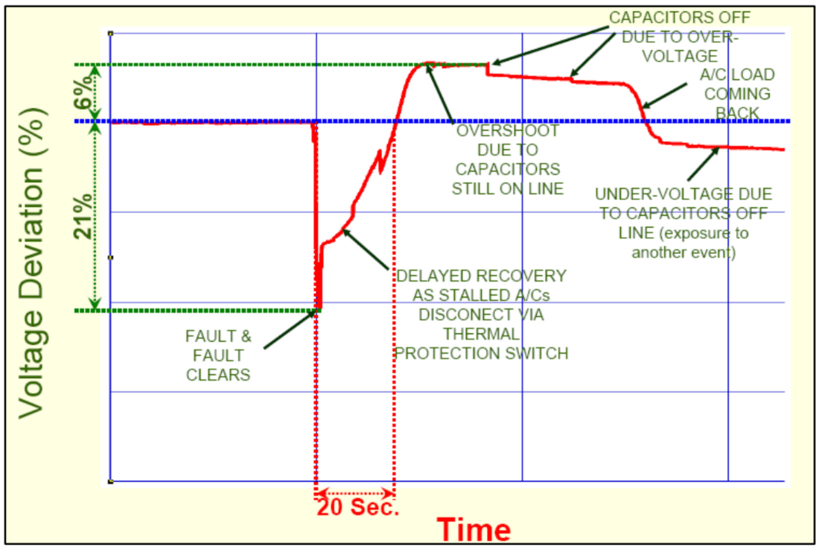
Single-phase Induction Motors

- SPIMs are a main type of residential loads, such as AC compressors
  - 13% (27%) in South Atlantic (Florida) [EIA'09]
- *Lack of* modeling and monitoring
  - Passive loads in distribution systems
  - No real-time observability
- More complicated than three-phase IMs because of asymmetric windings [Krause'65]

New Challenges

- Fault-induced delayed voltage recovery (FIDVR)

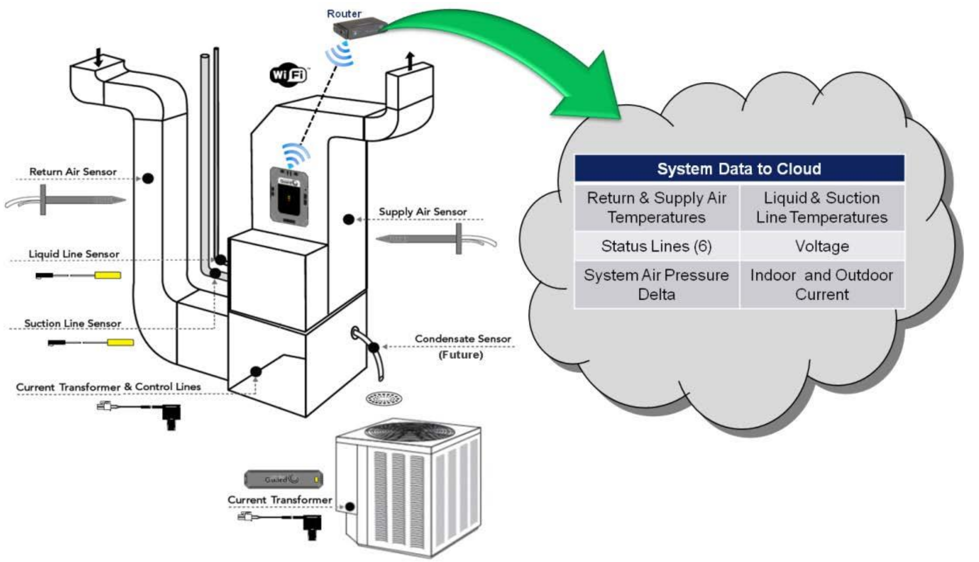


FIDVR illustration [NERC'2009].

- Aging capacitors are one main source of SPIM failures/stalling

New Opportunities

- Advanced sensing systems have been advocated to improve the reliability of SPIMs

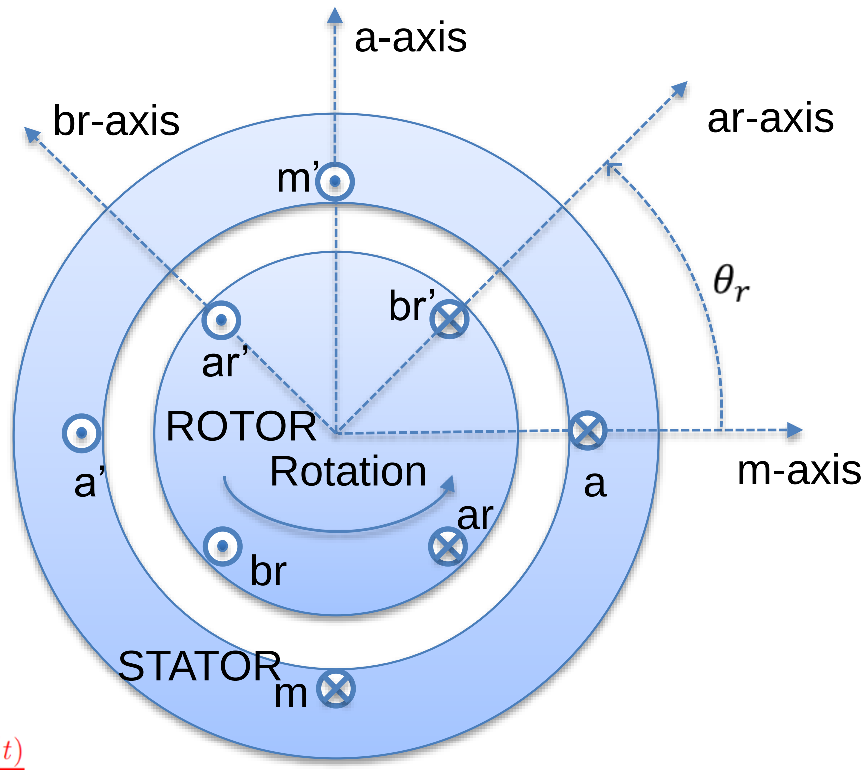


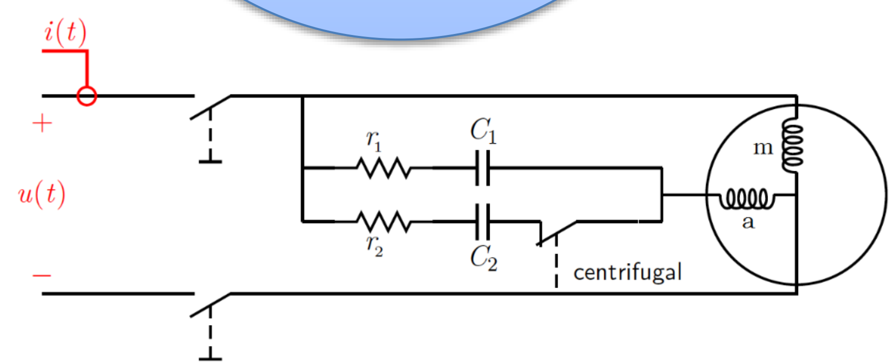
HVAC Fault Diagnostics and Detection (FDD) [Alsaleem et al'14]

- Non-intrusive monitoring of SPIMs using terminal measurements becomes possible

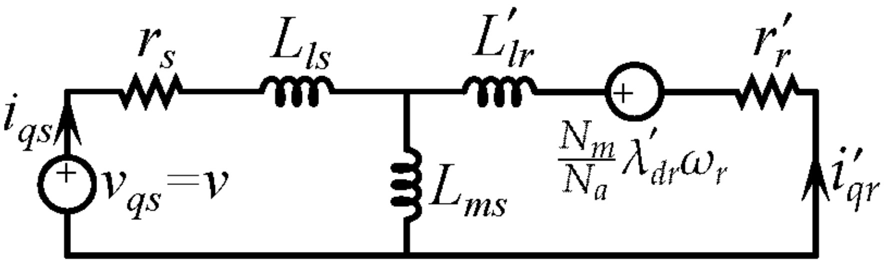
SPIM Winding Configuration

- Asymmetric stator windings (main/auxiliary)
- Identical rotor windings
- *dq* reference frame based transformation

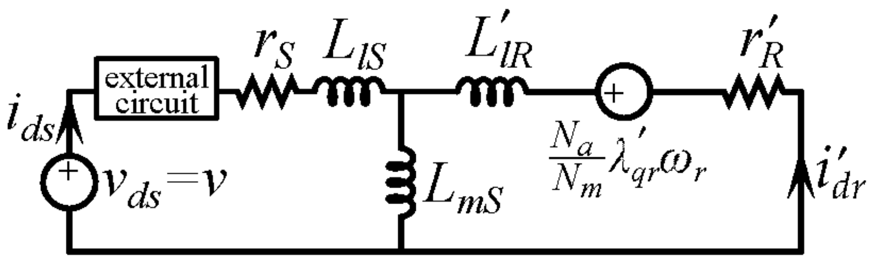




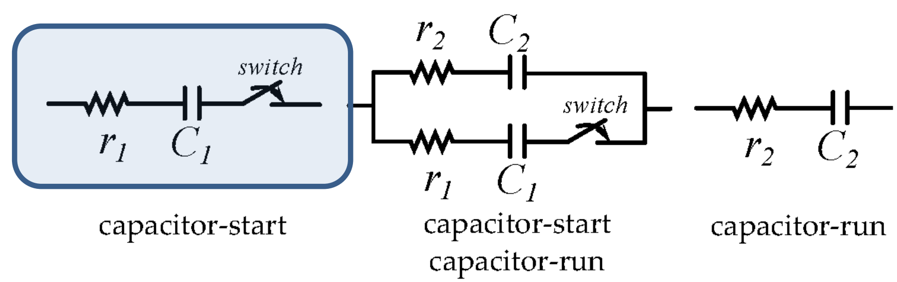
Equivalent Circuits



Main winding



Auxiliary winding



External circuit

- *Nonlinear* dynamics: current/speed variables

Dynamic Modeling

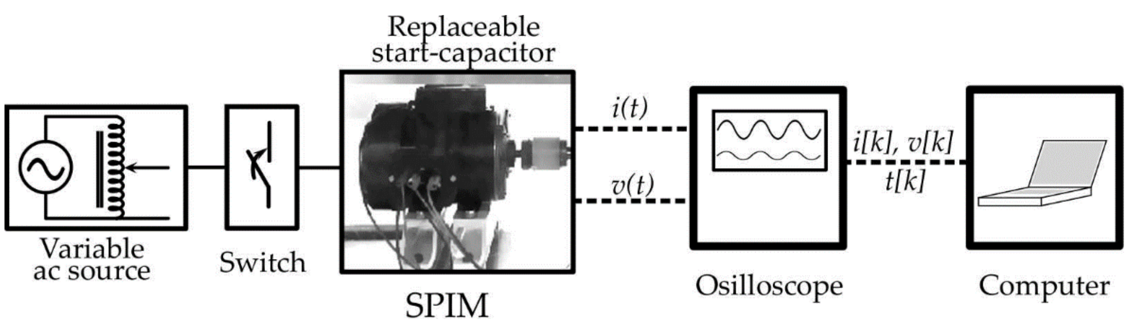
- To fit the transient data, we use a nonlinear least-squares (NLS) formulation to identify key SPIM parameters

$$\mathbf{p} = [r_s, r_S, r'_r, L_{ls}, L_{lS}, L_{ms}, n, J]$$

- Iterative solution provided by the Levenberg-Marquardt (L-M) algorithm
  - Combining the gradient descent and Gauss-Newton updates

Numerical and Lab Tests

- We tested the parameter estimation method using both simulated and real data
- Laboratory set-up with an SPIM fed by a variable single-phase ac source and connected to a data-acquisition-processing system



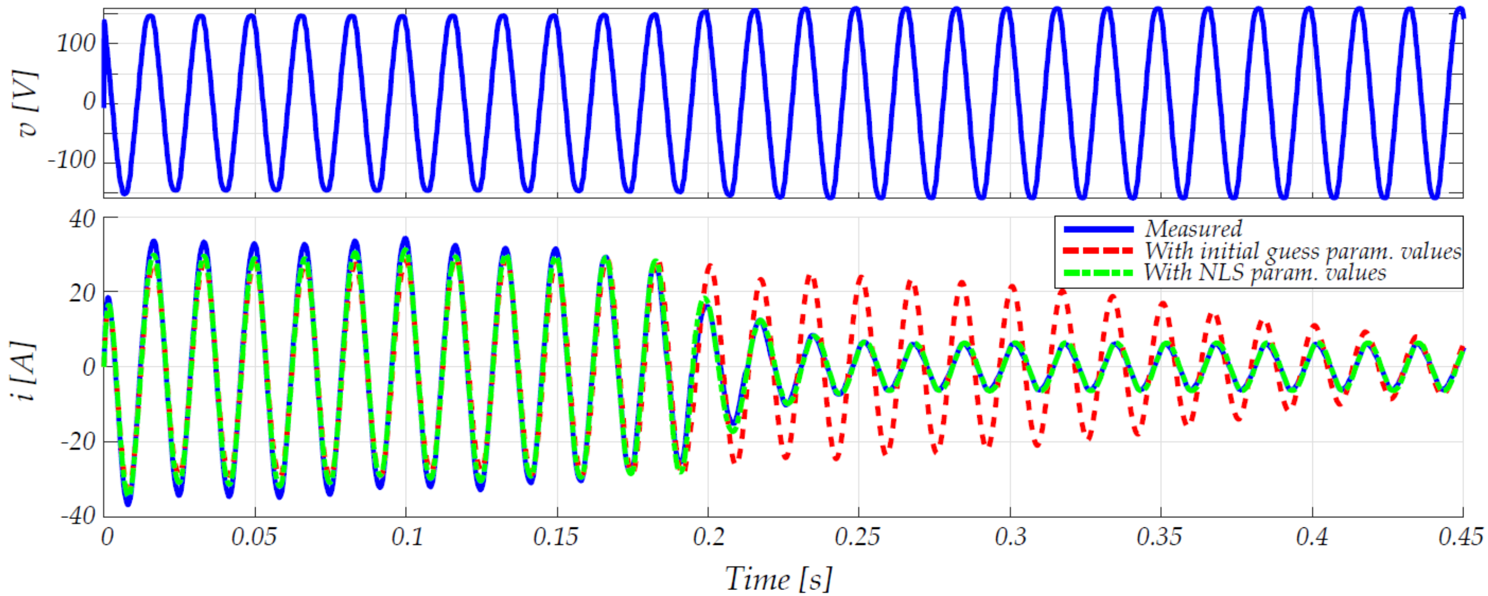
Simulated Data Fitting

- Minimal data fitting error with mismatch in the estimated parameter values

Parameter	Unit	Actual	Init. Guess	Est.
r_s	Ω	1.705	1.3640	1.2710
r_S	Ω	6.099	4.8792	4.8794
r'_r	Ω	1.9628	1.5702	1.5702
L_{ls}	mH	7.2	5.8	6.4
L_{lS}	mH	8.4	6.7	4.9
L_{ms}	mH	123.6	98.9	98.6
n		1.5840	1.2672	1.3363
J	$\mathrm{mg}\cdot\mathrm{m}^2$	2.044	1.640	2.282
$\psi(\mathrm{p})$		-	33.85	1.24

Real Data Fitting

- Initial guess computed using steady-state tests per IEEE standard procedure
- NLS estimates significantly improve data fitting



NLS Parameter Estimation

- Pro:
  - Perfect fit of input-output data
  - Better characterization of SPIM transient behaviors compared to steady-state tests
- Con:
  - Computation burden, not suitable for online implementation
  - Parameter identifiability issue

P. Huynh, H. Zhu, and D. Aliprantis, “Parameter estimation for single-phase induction motors using test measurement data,” *IEEE North American Power Symp. (NAPS), 2016*.

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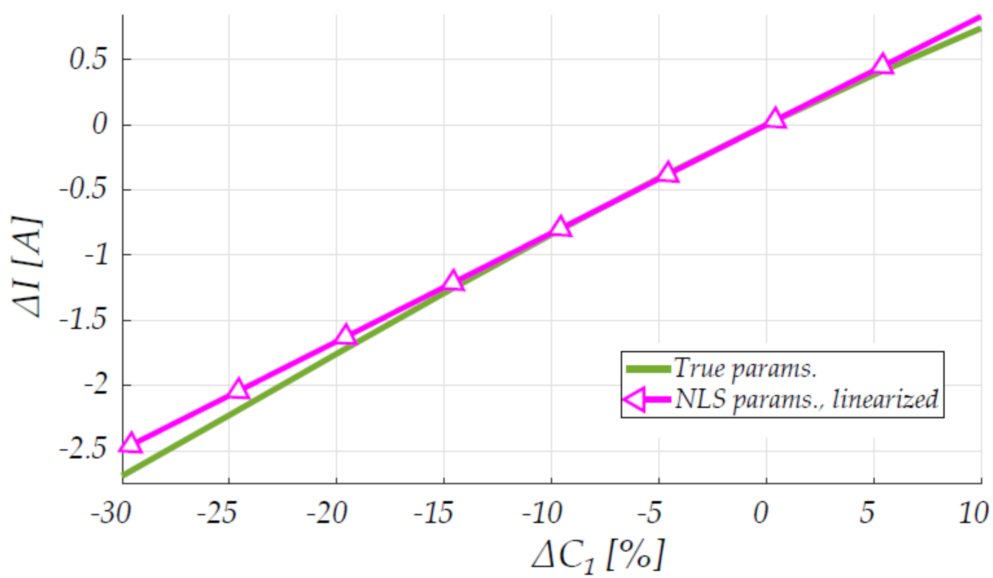
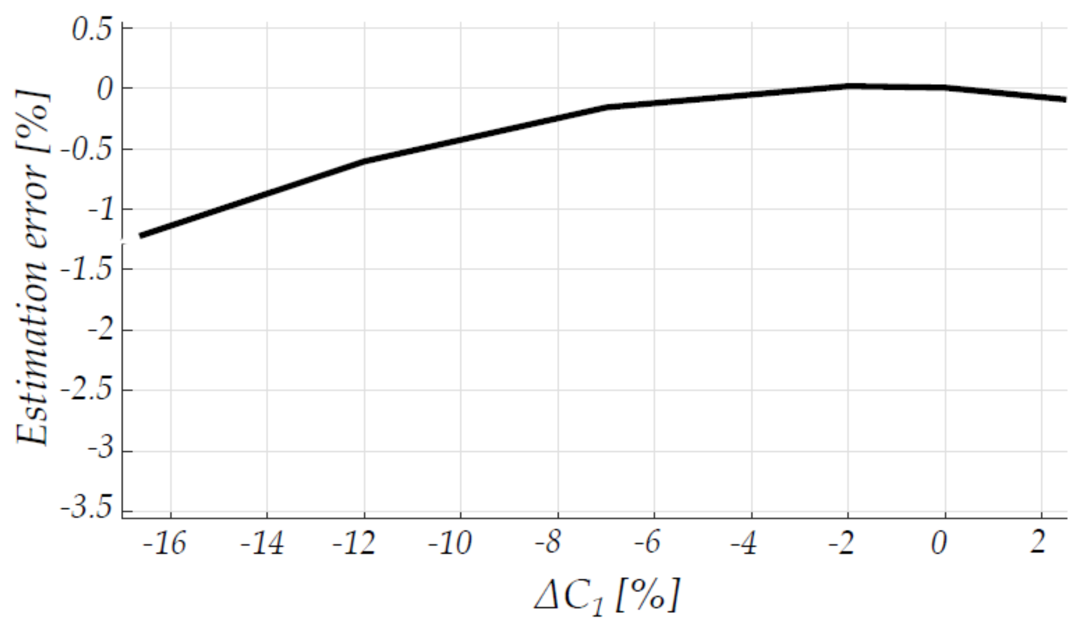
Estimating Capacitance Variation

- To efficiently track the variation of SPIM capacitance, we utilize a nearly linear $\Delta I - \Delta C$ relation based on SPIM circuit analysis



Numerical Validation

- <0.5% estimation error when capacitance value decreases within 10%



Lab Test Validation

- Nominal capacitance at 197.05 μF
- Estimated variation error ~ 1%, mainly due to the inaccuracy of the NLS-based $\Delta I - \Delta C$ curve

	Unit	Value	Value
Actual cap.	μF	190.2	185.3
Actual var.	%	-3.47	-5.96
Est. var. 1	%	-3.76	-6.19
Est. var. 2	%	-3.80	-5.93
Est. var. 3	%	-3.85	-5.85
Est. var. 4	%	-4.88	-7.23
Est. var. 5	%	-4.46	-7.17

Conclusions

- SPIM monitoring and prognostics crucial for modeling and operations of residential loads
- Possible to identify the SPIM dynamic model, but complicated due to the nonlinearity
- Efficient capacitor prognostics by relating to the current magnitude variation

Outlook

- Real system implementation for SPIM loads on the field
- Can we use the sensing capability of smart meters for SPIM modeling/prognostics?
- How to integrate with top-down load modeling at distribution feeder level?