Modeling Electrical Motor Dynamics using Encoder-Decoder with Recurrent Skip Connection

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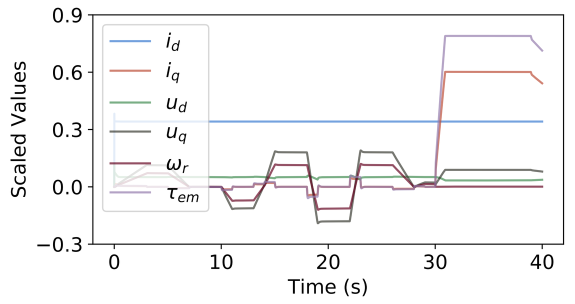
Modeling Complex Dynamics

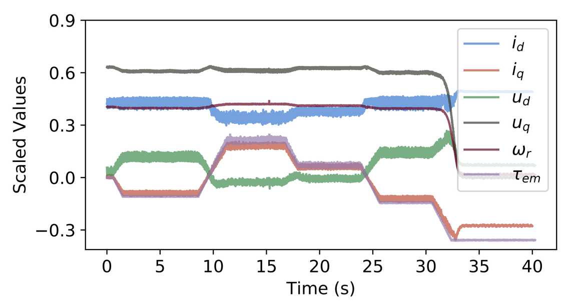
- Traditionally, electrical motor dynamics modeling relies on physics-based approach.
- Dynamics are dependent on several physical quantities and operating conditions.
- Sensors and estimators used for measuring these quantities come with inherent noise.
- This makes controller design and fault monitoring challenging problems.

Problem Statement

- We explore the feasibility of modeling the dynamics of an electrical motor by following a data-driven approach.
- We focus on modeling the relationship between input and output quantities of an induction motor.



Simulated sample



Real world sample

Related Work

- Physics of electrical motors and controller design [1, 2].
- State space model of an induction motor [3].
- Electrical motor dynamics modeling using analytical mechanics [4].
- Competitive performance of CNNs on sequential tasks [5].
- Independent Recurrent Neural Network [6].

Dataset

- 4 kW induction motor
- Acquisition rate: 250 Hz
- 7 quantities: $i_d, i_q, u_d, u_q, \omega_r, \omega_s, \tau_{em}$
- Simulated data: 100 hours, training: 70% and validation: 30%
- Raw data: 1207 seconds, no ω_s, 10 operating conditions, training: 20%, and testing: 80%

Proposed Architecture

Layer	Kernel Size	#Input Features	Input Length	#Ouput Features	Output Length
Conv1	10	3	100	32	91
Conv2	7	32	91	64	85
Conv3	5	64	85	128	81
Conv4	3	128	81	256	79

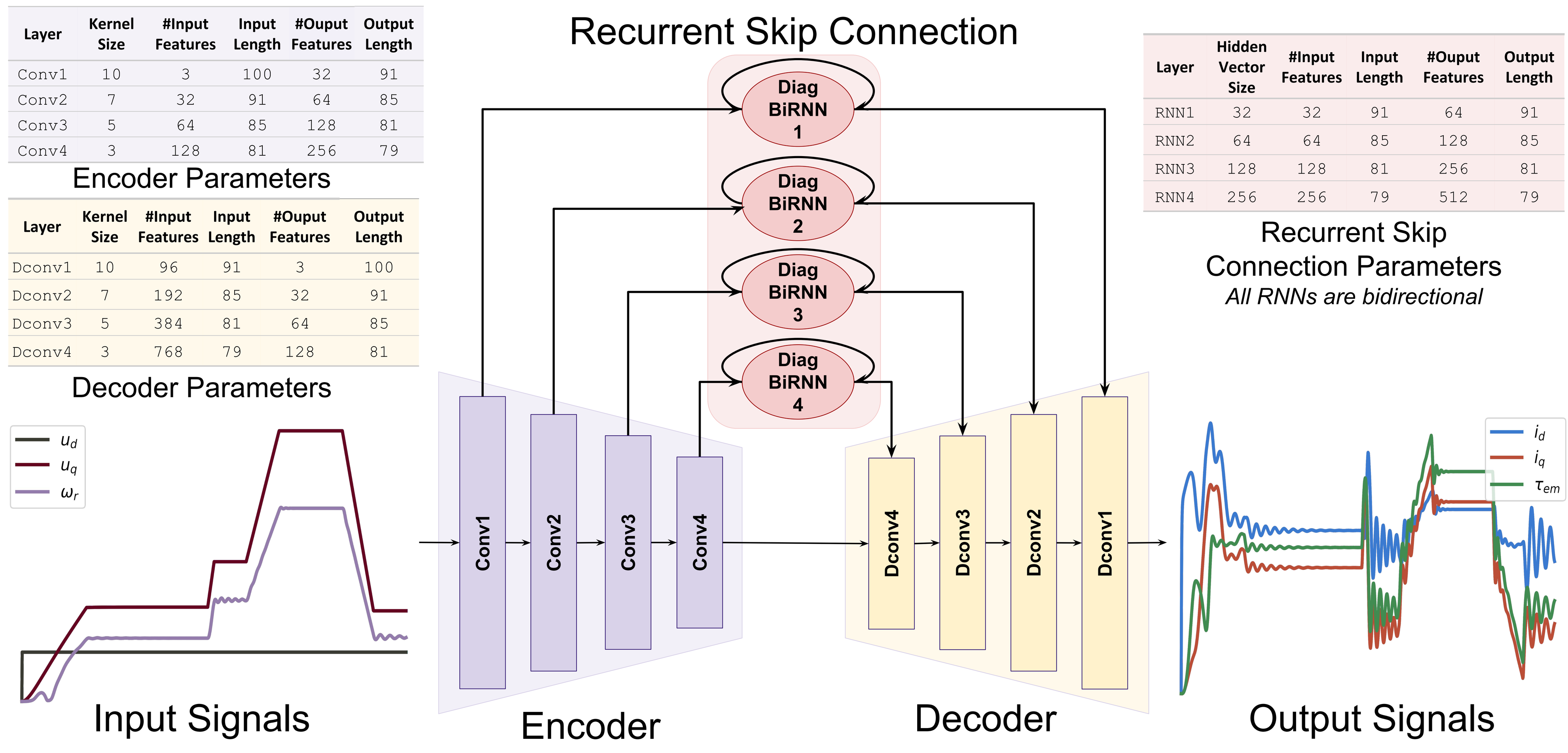
Encoder Parameters

Layer	Kernel Size	#Input Features	Input Length	#Ouput Features	Output Length
Dconv1	10	96	91	3	100
Dconv2	7	192	85	32	91
Dconv3	5	384	81	64	85
Dconv4	3	768	79	128	81

Decoder Parameters

Layer	Hidden Vector Size	#Input Features	Input Length	#Ouput Features	Output Length
RNN1	32	32	91	64	91
RNN2	64	64	85	128	85
RNN3	128	128	81	256	81
RNN4	256	256	79	512	79

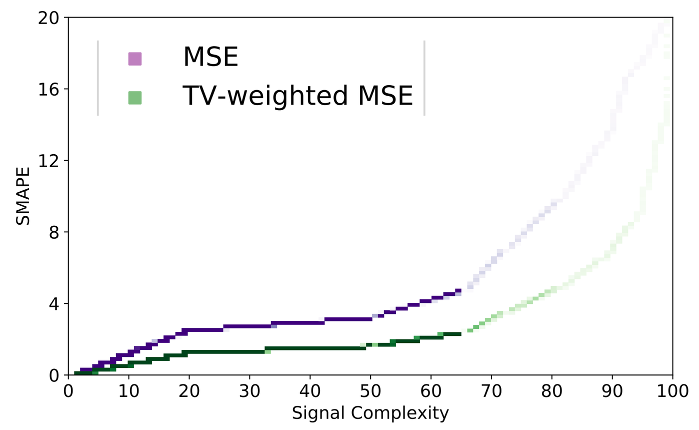
Recurrent Skip Connection Parameters
All RNNs are bidirectional



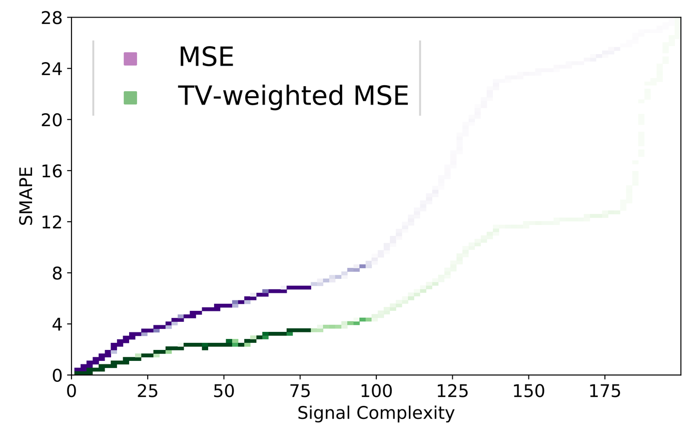
Results

Model	Window Size	Parameters	MAE	SMAPE	R^2
Feed-Forward	20	1118209	78.91	8.53%	-0.39
RNN	150	12001	78.26	7.76%	-0.35
LSTM	100	21889	79.58	6.29%	-0.11
CNN	100	650049	79.69	6.13%	-0.14
Encoder-Decoder	100	1096385	81.21	4.57%	0.29
Skip	100	364801	28.96	3.71%	0.42
RNN-Skip	100	638145	28.18	3.42%	0.43
BiRNN-Skip	100	967105	27.96	3.31%	0.41
DiagBiRNN-Skip	100	618465	**26.88**	**1.09%**	**0.95**

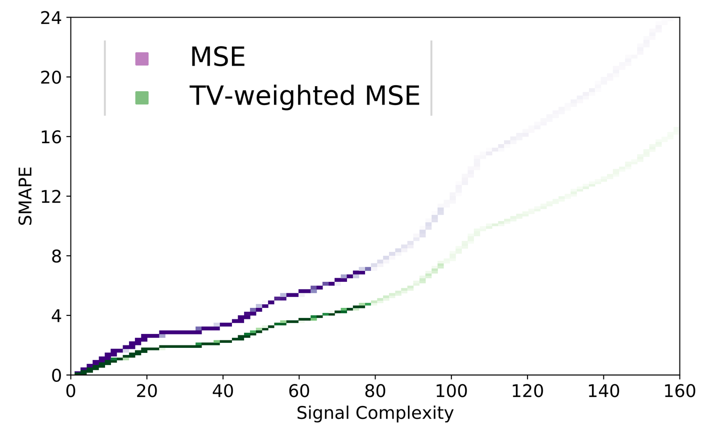
Results for the benchmark and the proposed model variants obtained on the simulated validation set.



(a) Current i_d

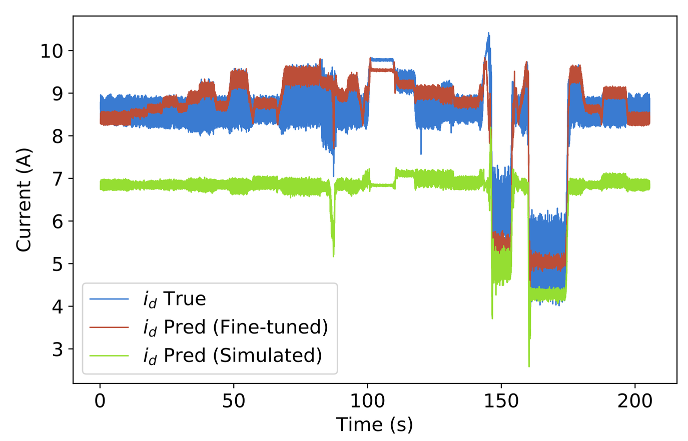


(b) Current i_q

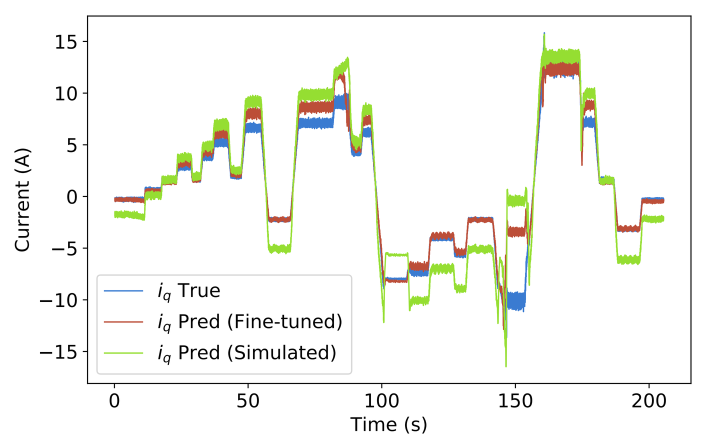


(c) Torque τ_{em}

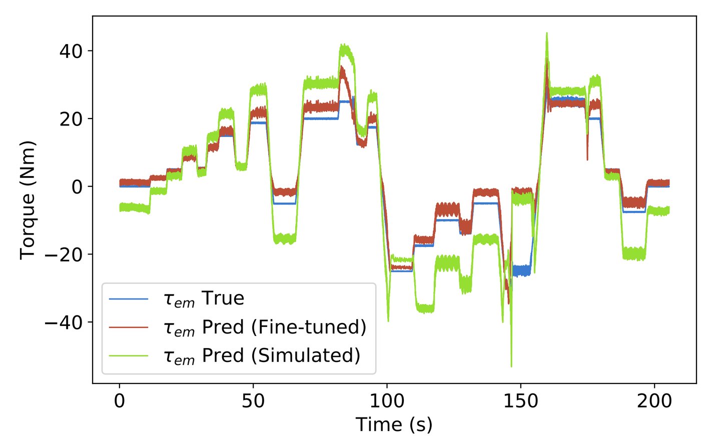
Comparison of simulated and fine-tuned model using SMAPE vs Signal Complexity(Total Variation) graph.



(a) Current i_d



(b) Current i_q



(c) Torque τ_{em}

Predicted result of one of the experiments from the test set.

Contributions

- New *Encoder-Decoder architecture* with *diagonalized recurrent skip connection* to effectively learn time-series relationship between different electrical quantities.

$$h_t = \tanh(w \odot x_t + u \odot h_{t-1} + b)$$

where $w \in \mathbb{R}^M$, $u \in \mathbb{R}^M$, and $b \in \mathbb{R}^M$ are input weights.

- A novel *loss function* that uses fast variations present in the electrical motor signals to avoid model bias.

$$\mathcal{L}_{\text{TV-MSE}} = \frac{1}{N}\sum_{i=1}^{N} \underbrace{\left(\sum_{t=1}^{T-1} |y_t^i - y_{t+1}^i|\right)}_{\text{Total Variation}} \overbrace{\left(\frac{1}{T}\sum_{t=1}^{T}(y_t^i - \hat{y}_t^i)^2\right)}^{\text{MSE}}$$

where y_t^i and $\hat{y}_t^i$ are the values of output and predicted sample i at time-step t, respectively. N is the number of training samples, where each sample is of duration T.

- *Two datasets*; a large dataset of simulated electrical motor operations and a small dataset of sensor data recorded from the real-world operations of electrical motors.

Visit project page for full paper, code, and dataset

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