



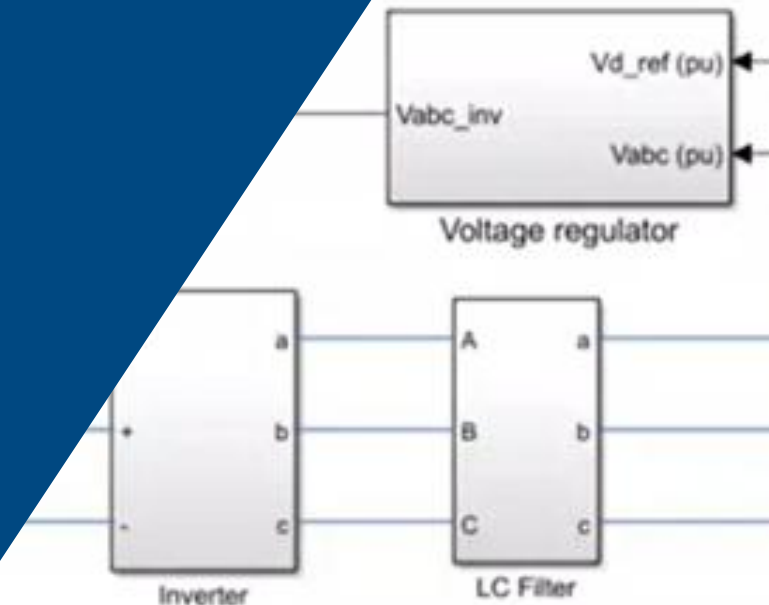
Predictive maintenance of power converters using simulated data

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MathWorks

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Application Engineering Group
MathWorks





Power Electronics Engineer



Data Scientist

Agenda

- Generate **power converter** aging data using Simscape
- Build AI models interactively for **predictive maintenance**
- Leverage **domain expertise** to enhance accuracy of predictive models
- **Deploy** predictive algorithm on hardware or cloud

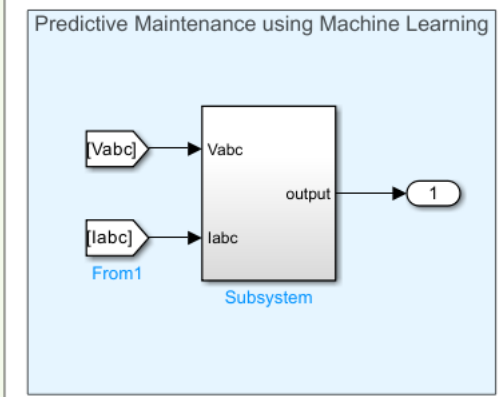
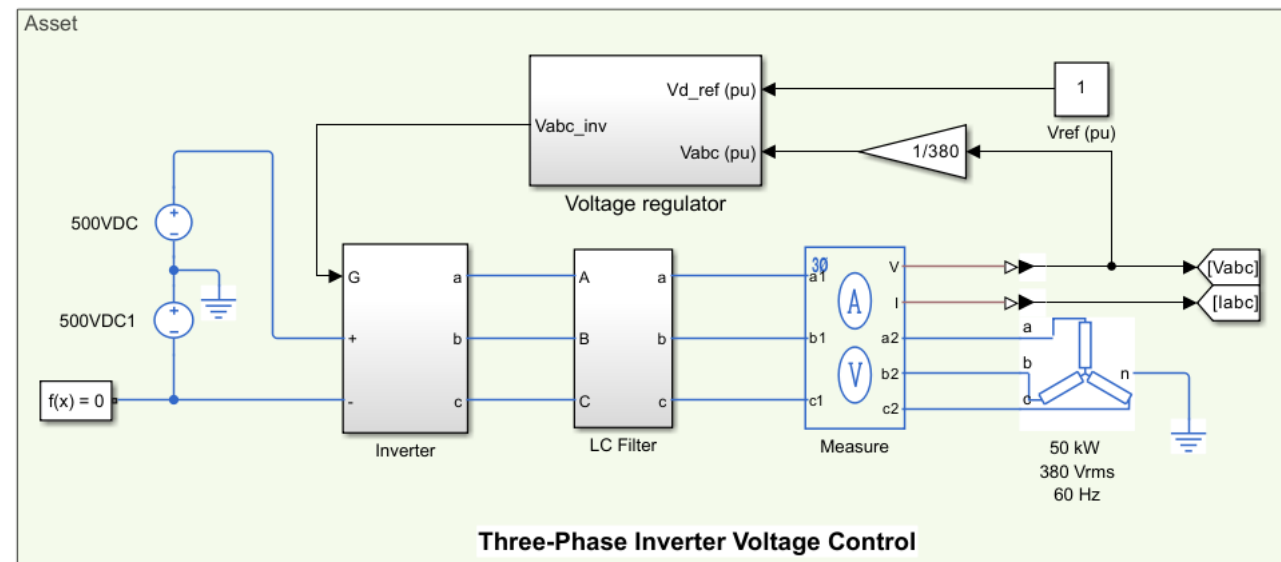
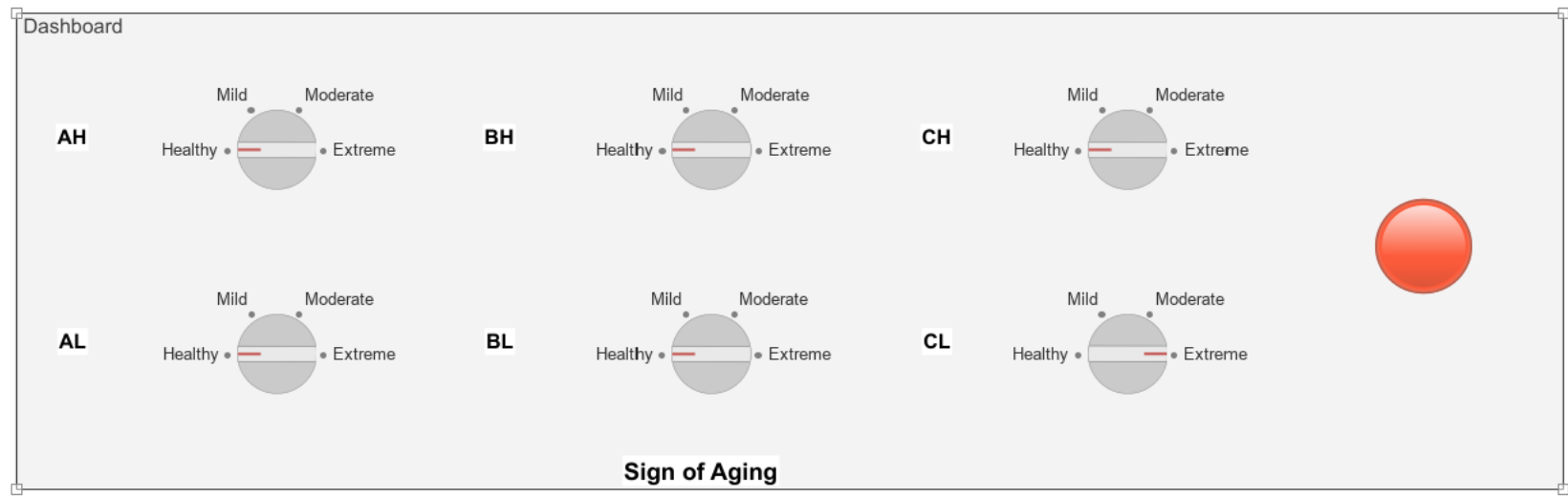
Test_3Ph_Inverter_Predictions * - Simulink

SIMULATION **DEBUG** **MODELING** **FORMAT** **APPS**

+ New Open Save Print FILE
 Library Browser Log Signals Add Viewer Signal Table PREPARE
 Stop Time: 0.095 Normal Fast Restart Step Back Run Step Forward Stop SIMULATE
 Data Inspector Logic Analyzer Bird's-Eye Scope Simulation Manager REVIEW RESULTS

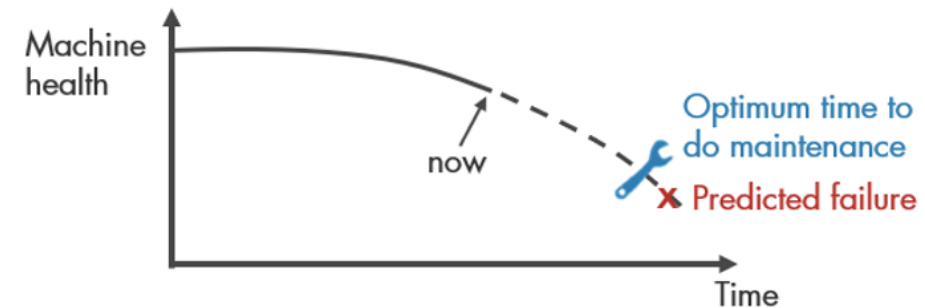
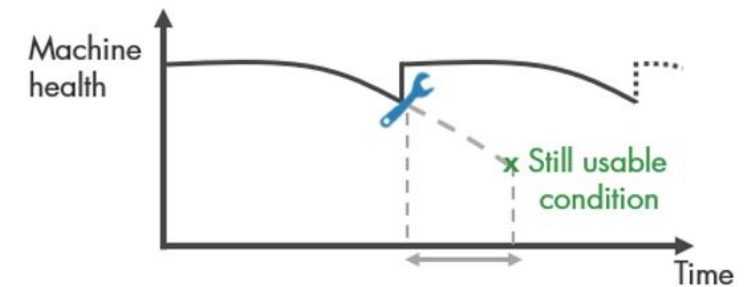
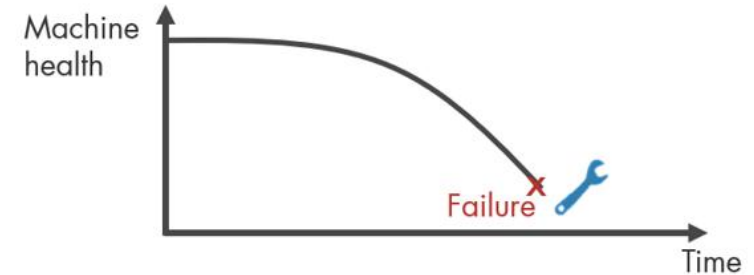
Test_3Ph_Inverter_Predictions

Test_3Ph_Inverter_Predictions



Types of Maintenance

- **Reactive** – Do maintenance once there's a problem
 - Problem: unexpected failures can be expensive and potentially dangerous
- **Scheduled** – Do maintenance at a regular rate
 - Problem: unnecessary maintenance can be wasteful; may not eliminate all failures
- **Predictive** – Forecast when problems will arise
 - Problem: difficult to make accurate forecasts for complex equipment



Many industries are applying predictive maintenance with MATLAB & Simulink today



Industrial Equipment

Atlas Copco



Food & Beverage

Coca-Cola



Oil & Gas

Baker Hughes



Manufacturing

Mondi



Renewable Energy

KIER



Electric Utilities

IMCORP



Robotics

Krones



Aerospace

All Nippon Airways

What does a predictive maintenance algorithm do?

Sensor Data



Algorithm



Prediction

Is my machine
operating
normally?

Anomaly Detection

I need help.

Why is my
machine behaving
abnormally?

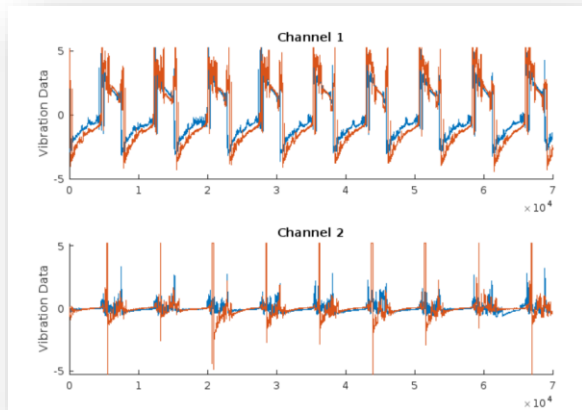
Fault Detection
(Diagnostics)

One of my cylinders
is blocked.

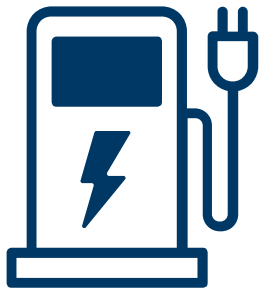
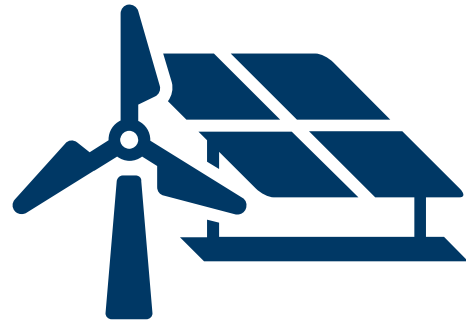
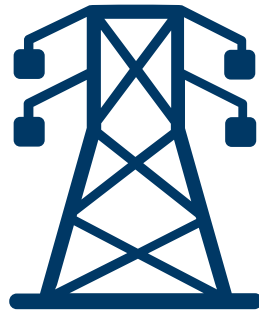
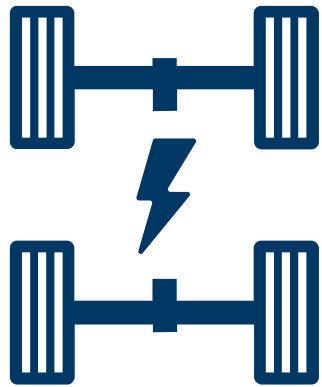
How much longer
can I operate my
machine?

Remaining Useful
Life Estimation
(Prognostics)

I will shut down your
line in 15 hours.

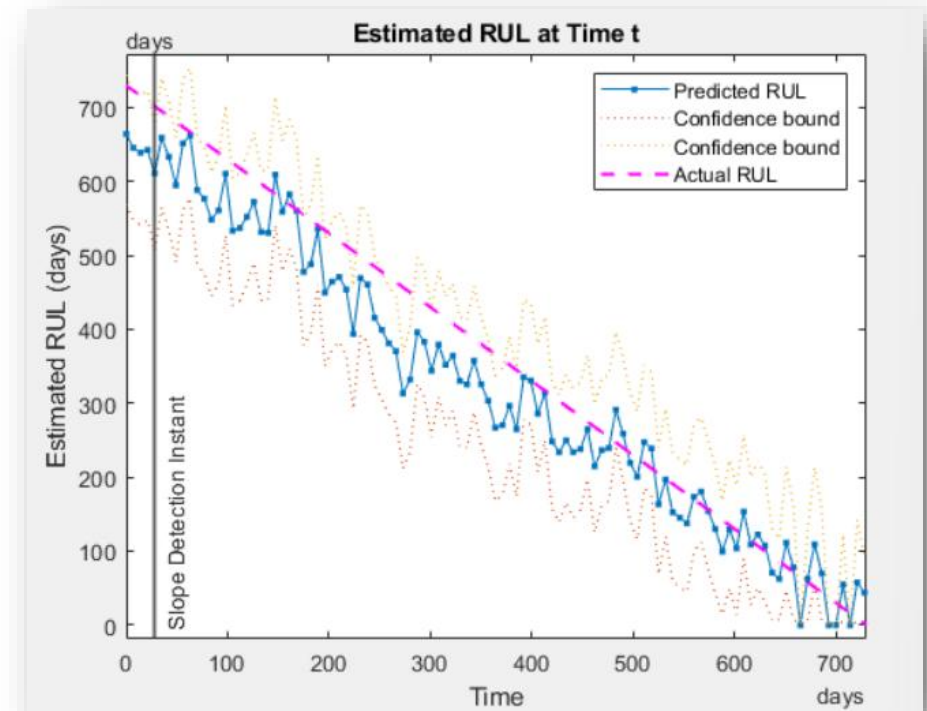


Power Converters – An Enabling Technology for More Electrification



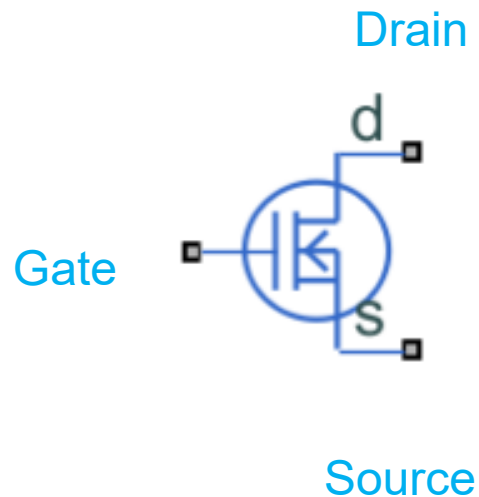
Why Power Converters Fail?

- Semiconductor Devices
- Electrolytic Capacitors
- Electrical Contacts
- Inductors
- Resistors
- Others



[Remaining Useful Life Estimation of a DC-Link Capacitor in a Power Converter](#)

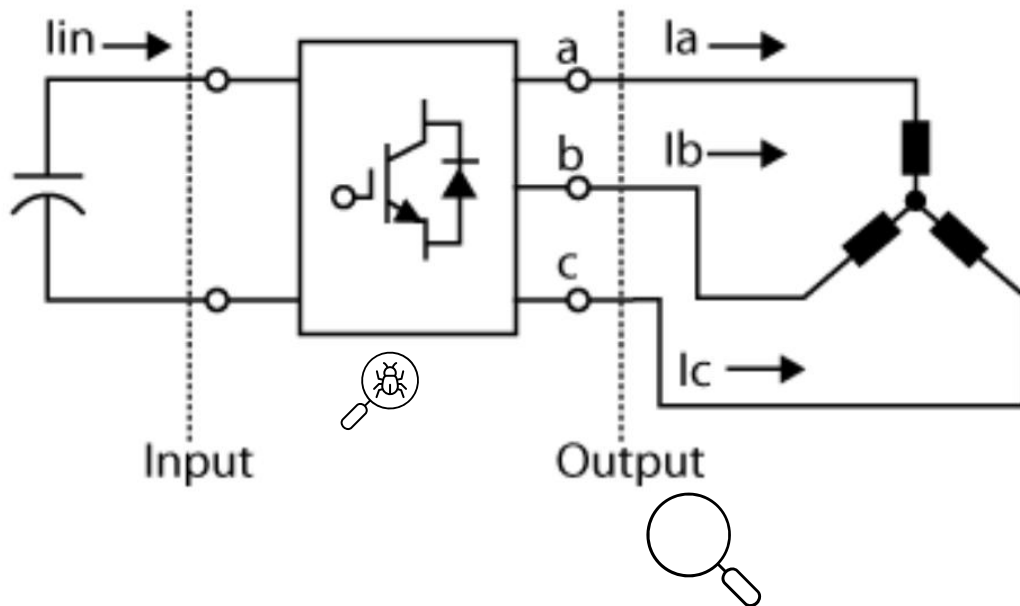
Failure Precursors of IGBTs



When IGBT ages, following parameter changes:

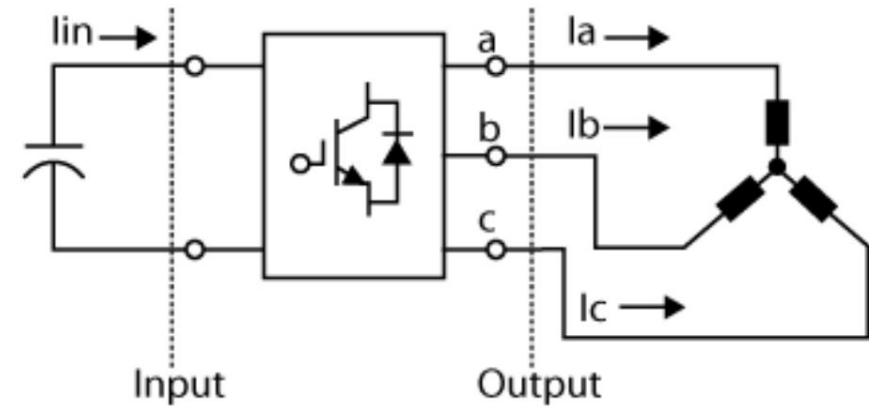
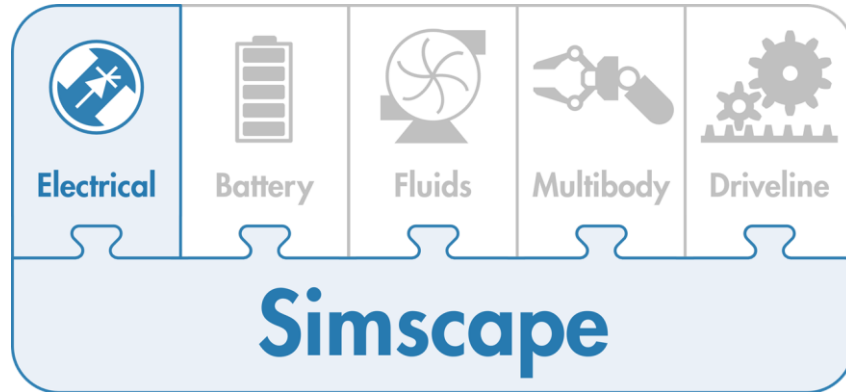
- Threshold Voltage
- Transconductance
- V_{CE} On / On-state Resistance

Failure Precursors of IGBTs

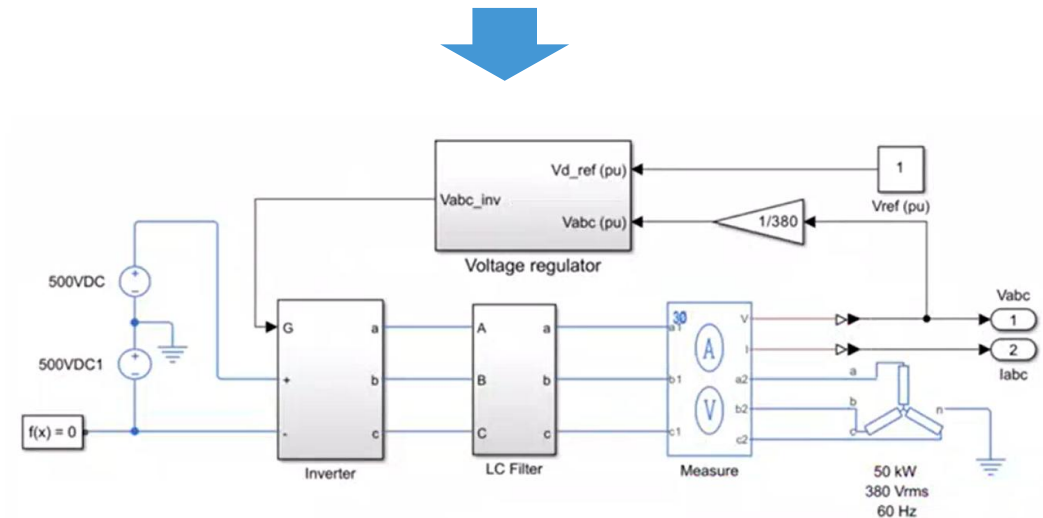


- Aging signs can be reflected in output voltage and current waveforms
- These signs may get diluted due to:
 - ✓ Measurement noise
 - ✓ Influence of other passive components (such as harmonic filter)

Model Faults in Power Converters and Generate Synthetic Data



- Simscape is a physical modeling tool
- Enables modeling and Simulation of Electronic, mechatronic, and electrical power systems



DEMO (Synthetic Data Generation)

Model Faults in Power Converters and Generate Synthetic Data

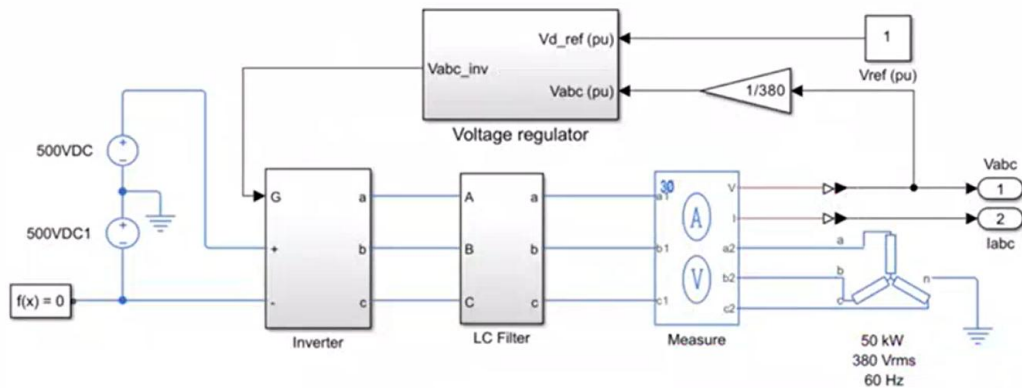
The screenshot displays the MATLAB/Simulink environment with a Simulink model titled "Multiple_Sim_Test_3Ph_Inverter". The model is a "Three-Phase Inverter Voltage Control" system. It includes a "Voltage regulator" block, an "Inverter" block, an "LC Filter" block, and a "Measure" block. The system is powered by two "500VDC" sources. The output of the inverter is connected to the LC filter, which is then connected to the measure block. The measure block outputs three-phase voltages (Vabc) and currents (Iabc). The system is configured to run multiple simulations (400) using the "SyntheticDataGenerati..." block.

The "Simulation Manager" window is open, showing the "Multiple Simulations - OnStateResistance" configuration. The "Run" column is checked, and the "Design Study" is "SyntheticDataGenerati...". The number of simulations is set to 400. The "Details: SyntheticDataGeneration" window is also open, showing the "Root Parameter Set" and "Parameter Set_1". The parameters are listed in the table below:

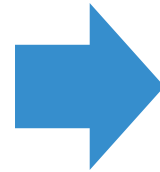
Type	Name	Value
Model Parameter	SimulationMode	normal
Variable	RaH	0.0066
Variable	RaL	0.0060
Variable	RbH	0.0055
Variable	RbL	0.0068
Variable	RcH	0.0059
Variable	RcL	0.0065

The "Simulation Manager" window also shows the "Simulation Details" section, which includes a table of simulation results. The table has columns for "Run ID", "Status", "Progress", "Elapsed Time", "Parameters", "Timing Info", and "Diagnostics". The simulation is currently running, and the progress bar shows 0% completion.

Simulated ageing of power converters to generate synthetic data



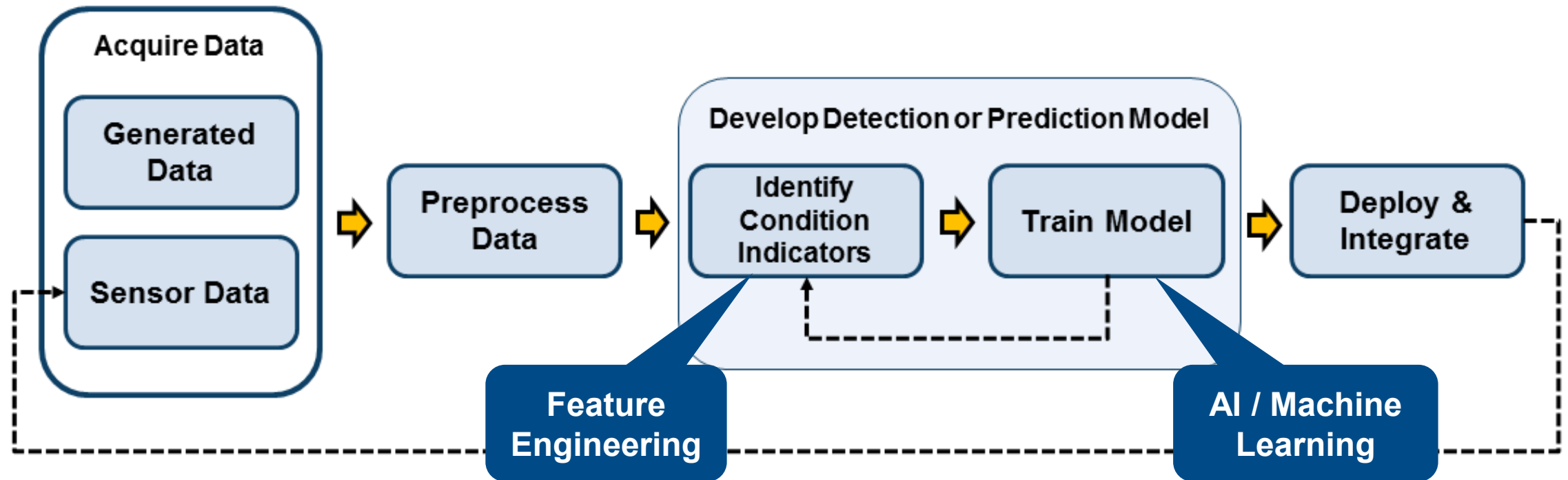
~ 5% change = 'Healthy'
 ~ 6 - 11% change = 'Mild'
 ~ 12 - 18% change = 'Moderate'
 ~ more than 18% change = 'Extreme'



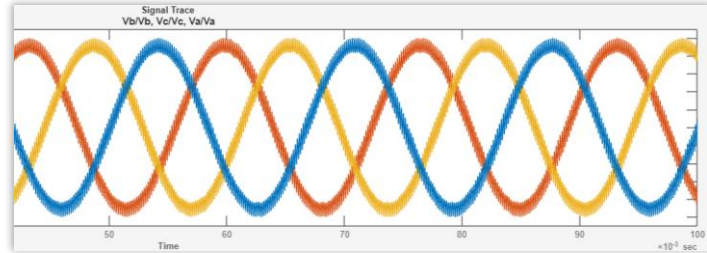
```
Test_data_Healthy_file_2
Test_data_Healthy_file_3
Test_data_Healthy_file_4
Test_data_Healthy_file_5
Test_data_Healthy_file_6
Test_data_Healthy_file_7
Test_data_Healthy_file_8
Test_data_Healthy_file_9
Test_data_fault_in_phaseAH_Sign_of_Aging_Extreme_file_11
Test_data_fault_in_phaseAH_Sign_of_Aging_Extreme_file_5
Test_data_fault_in_phaseAH_Sign_of_Aging_Mild_file_1
Test_data_fault_in_phaseAH_Sign_of_Aging_Mild_file_7
Test_data_fault_in_phaseAH_Sign_of_Aging_Moderate_file_3
Test_data_fault_in_phaseAH_Sign_of_Aging_Moderate_file_9
Test_data_fault_in_phaseAL_Sign_of_Aging_Extreme_file_12
Test_data_fault_in_phaseAL_Sign_of_Aging_Extreme_file_6
Test_data_fault_in_phaseAL_Sign_of_Aging_Mild_file_2
Test_data_fault_in_phaseAL_Sign_of_Aging_Mild_file_8
Test_data_fault_in_phaseAL_Sign_of_Aging_Moderate_file_10
Test_data_fault_in_phaseAL_Sign_of_Aging_Moderate_file_4
Test_data_fault_in_phaseBH_Sign_of_Aging_Extreme_file_11
Test_data_fault_in_phaseBH_Sign_of_Aging_Extreme_file_5
Test_data_fault_in_phaseBH_Sign_of_Aging_Mild_file_1
Test_data_fault_in_phaseBH_Sign_of_Aging_Mild_file_7
Test_data_fault_in_phaseBH_Sign_of_Aging_Moderate_file_3
Test_data_fault_in_phaseBH_Sign_of_Aging_Moderate_file_9
Test_data_fault_in_phaseBL_Sign_of_Aging_Extreme_file_12
Test_data_fault_in_phaseBL_Sign_of_Aging_Extreme_file_6
Test_data_fault_in_phaseBL_Sign_of_Aging_Mild_file_2
Test_data_fault_in_phaseBL_Sign_of_Aging_Mild_file_8
Test_data_fault_in_phaseBL_Sign_of_Aging_Moderate_file_10
Test_data_fault_in_phaseBL_Sign_of_Aging_Moderate_file_4
Test_data_fault_in_phaseCH_Sign_of_Aging_Extreme_file_11
```

...
 ...

Predictive Maintenance Algorithm Development Workflow



Data Preparation



Current / Voltage Profile

	Time	Va	Vb	Vc	Ia	Ib	Ic				
1	0	-8.6331e-28	-268.7005	268.7005	-2.9893e-28	-93.0403	93.0403				
2	1.0000e-06	-0.0534	-263.7545	263.6477	-0.0185	-91.3277	91.2908				
3	2.0000e-06	-0.1591	-258.9257	258.6075	-0.0551	-89.6557	89.5455				
4	3.0	Time	Va	Vb	Vc	Ia	Ib	Ic			
5	4	1	0	-8.6331e-28	-268.7005	268.7005	-2.9893e-28	-93.0403	93.0403		
6	5	2	1.0000e-06	-0.0534	-263.7545	263.6477	-0.0185	-91.3277	91.2908		
7	6	3	2.0000e-06	-0.1591	-258.9257	258.6075	-0.0551	-89.6557	89.5455		
8	7	4	3.0	Time	Va	Vb	Vc	Ia	Ib	Ic	
9	8	5	4.0	1	0	-8.6331e-28	-268.7005	268.7005	-2.9893e-28	-93.0403	93.0403
10	9	6	5.0	2	1.0000e-06	-0.0534	-263.7545	263.6477	-0.0185	-91.3277	91.2908
11	10	7	6.0	3	2.0000e-06	-0.1591	-258.9257	258.6075	-0.0551	-89.6557	89.5455
12	11	8	7.0	4	3.0000e-06	-0.3161	-254.2123	253.5801	-0.1095	-88.0237	87.8047
13	12	9	8.0	5	4.0000e-06	-0.5236	-249.6129	248.5658	-0.1813	-86.4311	86.0685
14	13	10	9.0	6	5.0000e-06	-0.7804	-245.1257	243.5649	-0.2702	-84.8773	84.3369
15	14	11	1.0	7	6.0000e-06	-1.0858	-240.7491	238.5776	-0.3760	-83.3619	82.6100
16	15	12	1.1	8	7.0000e-06	-1.4386	-236.4816	233.6044	-0.4981	-81.8842	80.8879
17	16	13	1.2	9	8.0000e-06	-1.8381	-232.3216	228.6454	-0.6365	-80.4438	79.1708
18	17	14	1.3	10	9.0000e-06	-2.2833	-228.2674	223.7008	-0.7906	-79.0400	77.4587
19	18	15	1.4	11	1.0000e-05	-2.7733	-224.3177	218.7711	-0.9603	-77.6723	75.7518
20	19	16	1.5	12	1.1000e-05	-3.3072	-220.4708	213.8564	-1.1451	-76.3403	74.0500
21	20	17	1.6	13	1.2000e-05	-3.8841	-216.7252	208.9569	-1.3449	-75.0433	72.3535
22	21	18	1.7	14	1.3000e-05	-4.5033	-213.0795	204.0730	-1.5593	-73.7810	70.6624
23	22	19	1.8	15	1.4000e-05	-5.1637	-209.5322	199.2047	-1.7880	-72.5527	68.9767
24	23	20	1.9	16	1.5000e-05	-5.8647	-206.0819	194.3525	-2.0307	-71.3580	67.2966
25	24	21	2.0	17	1.6000e-05	-6.6053	-202.7270	189.5164	-2.2871	-70.1963	65.6220
26	25	22	2.1	18	1.7000e-05	-7.3847	-199.4663	184.6968	-2.5570	-69.0673	63.9532
27	26	23	2.2	19	1.8000e-05	-8.2022	-196.2982	179.8938	-2.8401	-67.9703	62.2901
28	27	24	2.3	20	1.9000e-05	-9.0569	-193.2214	175.1076	-3.1361	-66.9049	60.6328
29	28	25	2.4	21	2.0000e-05	-9.9481	-190.2346	170.3384	-3.4446	-65.8707	58.9814
	26	25	2.2	21	2.1000e-05	-10.8750	-187.3364	165.5864	-3.7656	-64.8672	57.3360
	27	26	23	22	2.2000e-05	-11.8367	-184.5253	160.8519	-4.0986	-63.8938	55.6966
	28	27	24	23	2.3000e-05	-12.8327	-181.8002	156.1349	-4.4434	-62.9502	54.0633
	29	28	25	24	2.4000e-05	-13.8620	-179.1597	151.4357	-4.7999	-62.0359	52.4362
		26	25	2.5	2.5000e-05	-14.9241	-176.6026	146.8613	-5.1676	-61.1505	50.8523
		27	26	0.0000e-05	-16.0181	-174.1274	142.4099	-5.5464	-60.2934	49.3109	
		28	27	0.0000e-05	-17.1433	-171.7330	138.0795	-5.9361	-59.4643	47.8115	
		29	28	0.0000e-05	-18.2991	-169.4182	133.8685	-6.3363	-58.6628	46.3534	

Multiple Readings

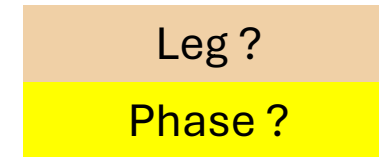
Anomaly Detection



Ageing Severity



Ageing Localization



48x12 table

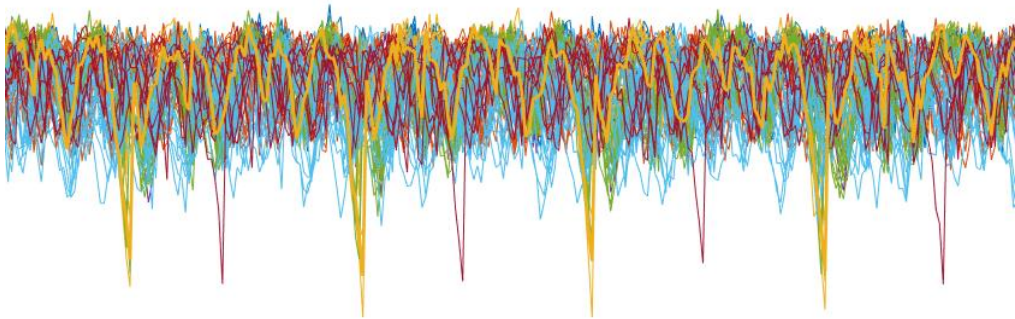
	1	2	3	4	5	6	7	8	9	10	11	12
	Va	Vb	Vc	Ia	Ib	Ic	ageingDetected	ageingSeverity	ageingPhase	ageingLeg	ageingPhaseLeg	fileURI
11	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		0 healthy	"NA"	"NA"	"	"C:\Users\s...
12	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		0 healthy	"NA"	"NA"	"	"C:\Users\s...
13	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 extreme	"A"	"H"	'AH'	"C:\Users\s...
14	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 extreme	"A"	"H"	'AH'	"C:\Users\s...
15	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 mild	"A"	"H"	'AH'	"C:\Users\s...
16	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 mild	"A"	"H"	'AH'	"C:\Users\s...
17	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 moderate	"A"	"H"	'AH'	"C:\Users\s...
18	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 moderate	"A"	"H"	'AH'	"C:\Users\s...

Ensemble dataset

Feature extraction

48x12 table

	1 Va	2 Vb	3 Vc	4 Ia	5 Ib	6 Ic	7 ageingDetected	8 ageingSeverity
11	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		0 healthy
12	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		0 healthy
13	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 extreme
14	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 extreme
15	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 mild
16	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 mild
17	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 moderate
18	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...	90000x1 ti...		1 moderate



- Signal statistics

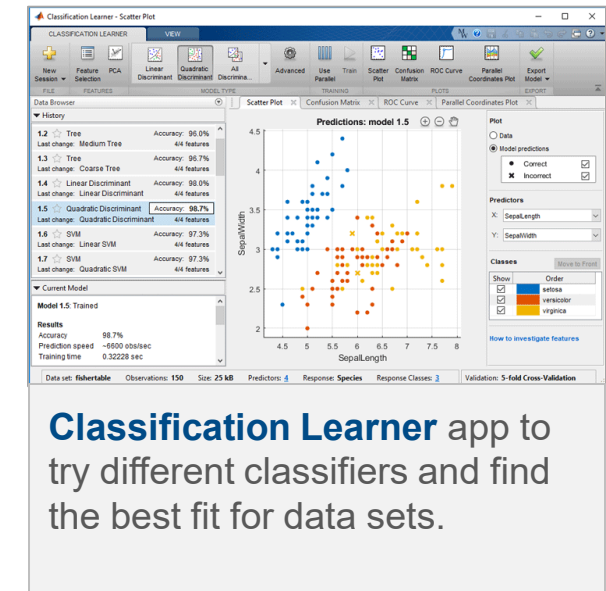
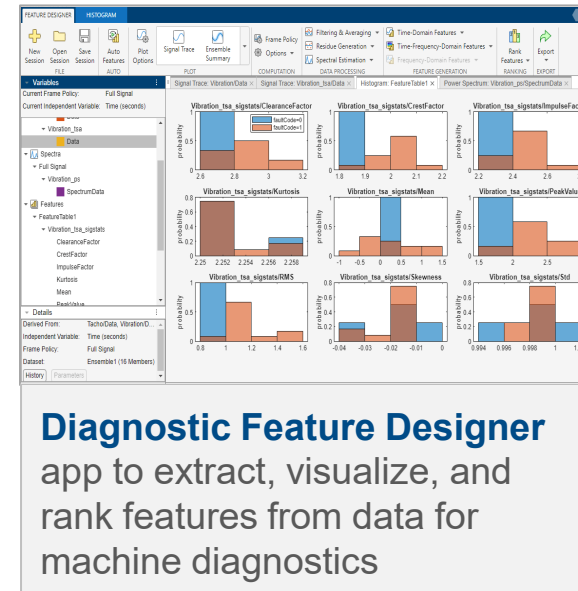
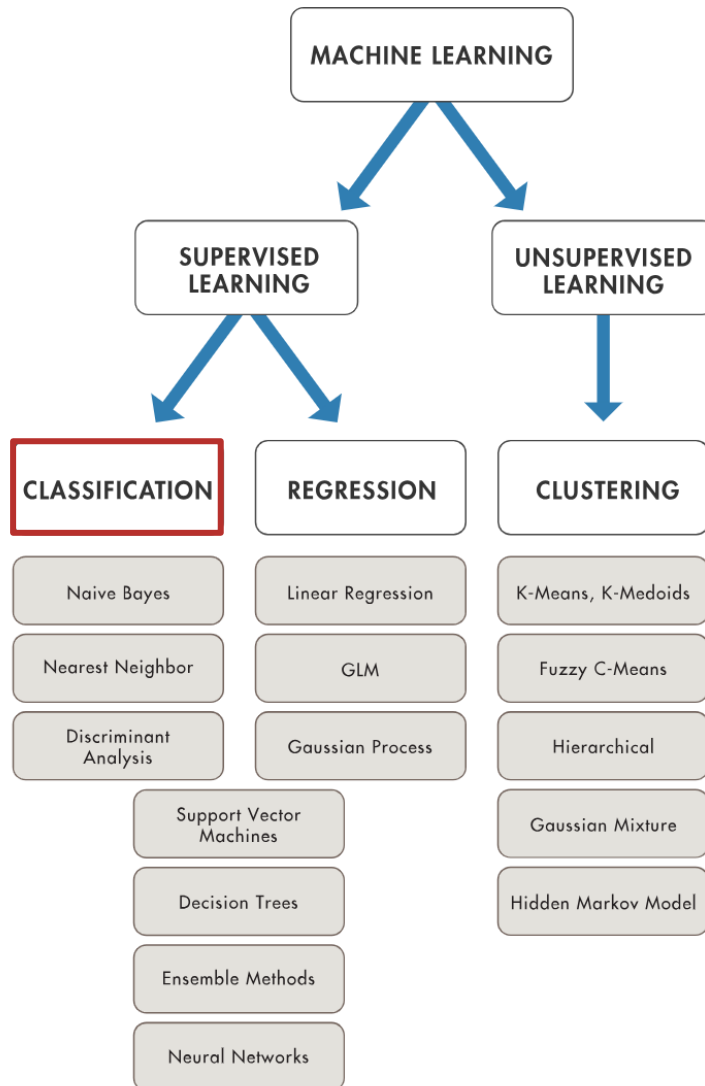
- Mean
- Signal-to-noise ratio
- Peak frequency
- ...

Condition Indicators/
Health Indicators/
Features

- Data fusion and transformation

- Principal component analysis
- Regression
- Normalization
- ...

Building an AI Model



Building an AI-based ageing classification algorithm



Power Electronics Engineer



Data Scientist

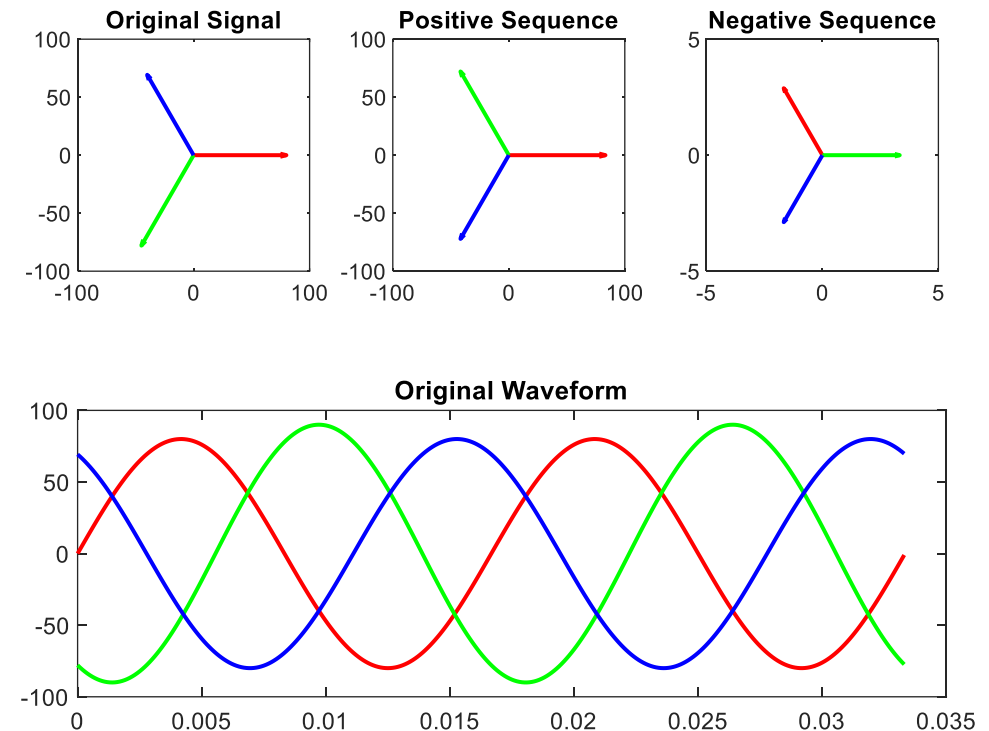
Signal Features -> Machine Learning

Accuracy: 90%+ ✓

Sequence Component Analysis of 3-phase Signal

$$\begin{matrix} V_{zero} \\ V_{positive} \\ V_{negative} \end{matrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Where, $a = 1 \angle 120^\circ$



Leveraging domain expertise to handle noise



Power Electronics Engineer

Domain expertise
Sequence component analysis
Accuracy: 80%+ ✓



Data Scientist

Signal Features -> Machine Learning
Accuracy: 90%+
With noise: 65% ✗

Leveraging domain expertise to build a better AI algorithm!



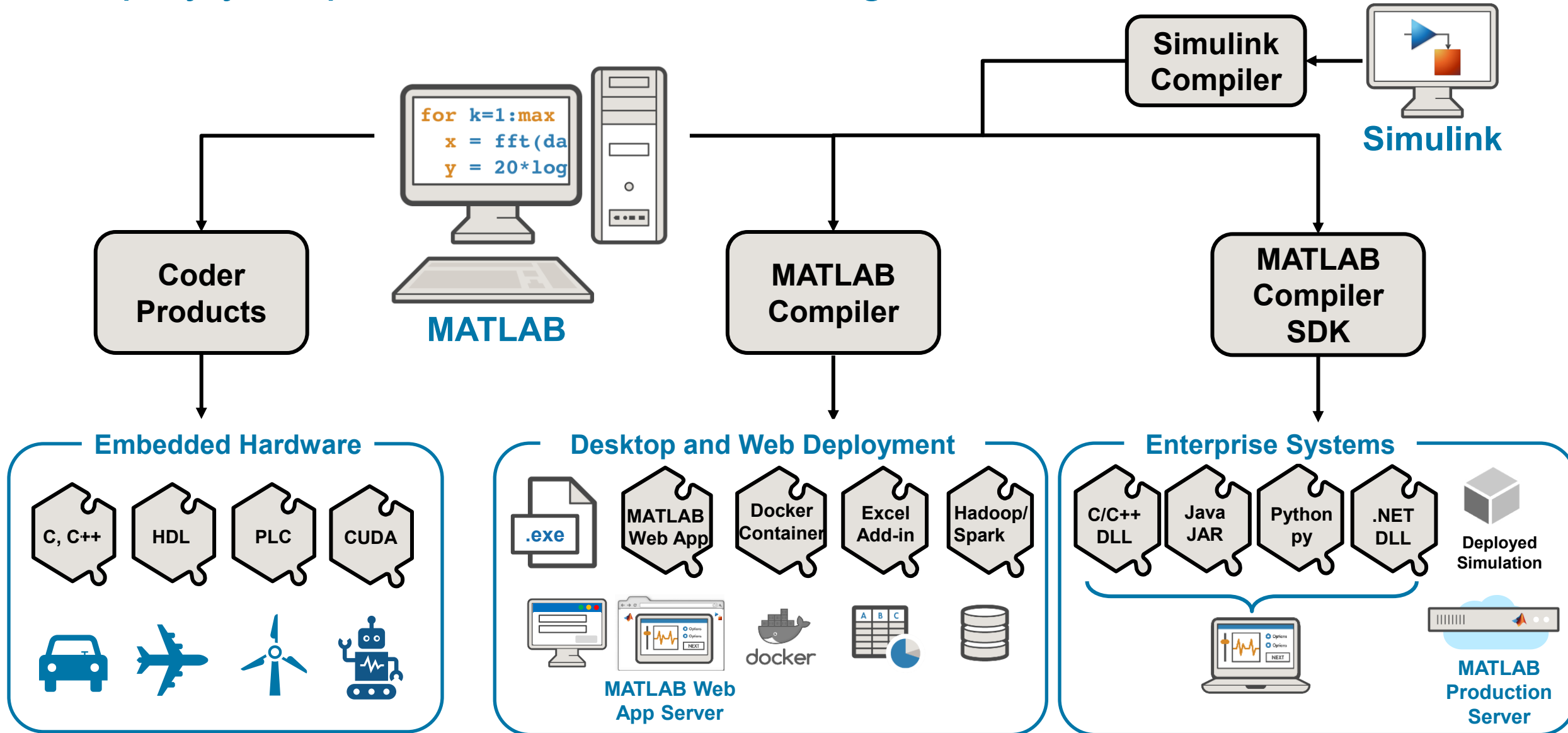
Power Electronics Engineer



Data Scientist

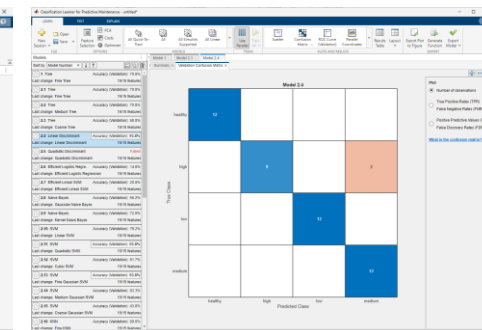
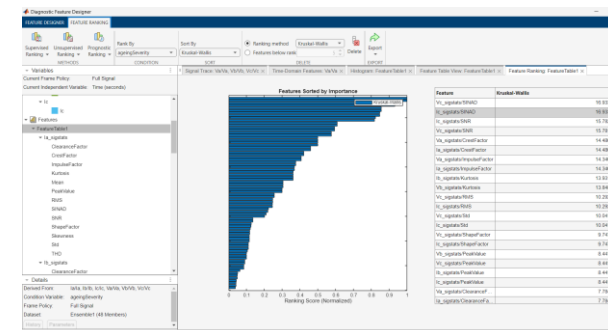
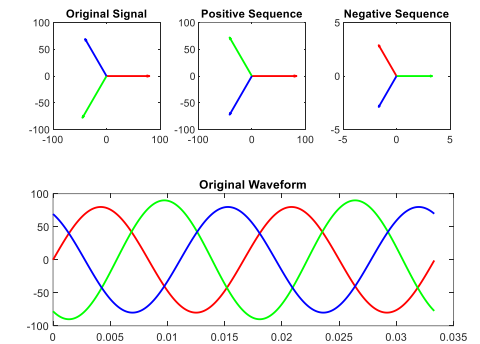
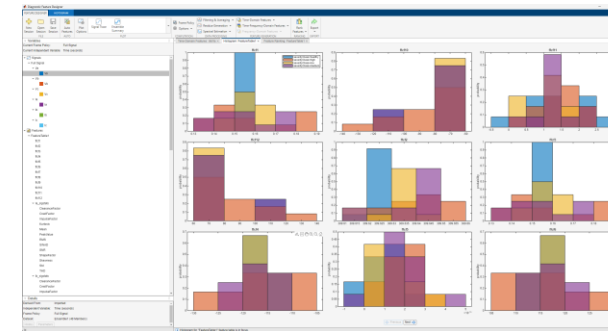
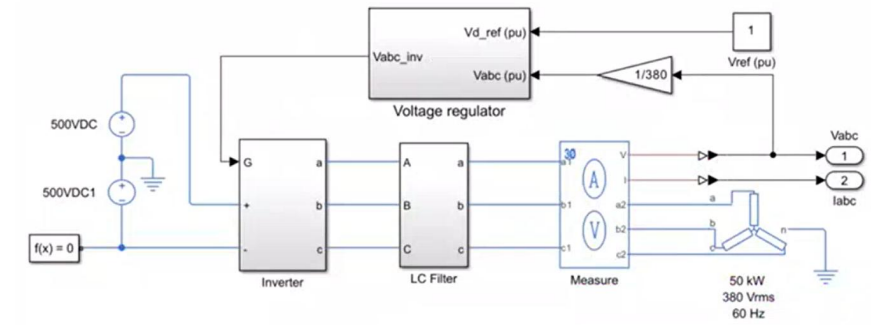
Domain expertise + Machine Learning
Sequence component analysis + Signal statistics
Accuracy: 90%+ ✓

Deploy your predictive maintenance algorithms



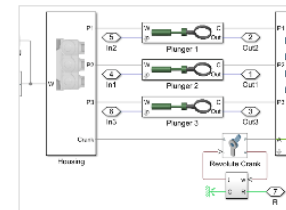
Key Takeaways

- **Generate** power converter ageing data using Simscape
- Build AI models interactively for **predictive maintenance**
- Leverage **domain expertise** to enhance accuracy of predictive models
- **Deploy** predictive algorithm on hardware or cloud



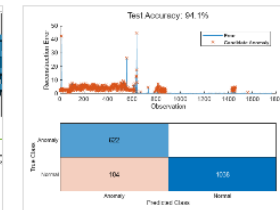
A library of reference examples helps you get started quickly

- **Templates** for predictive maintenance algorithms
- **Topics cover**
 - Data acquisition and management
 - Data preprocessing
 - Feature engineering
 - Machine learning model training
 - Deployment
- **Reuse as starting points** for your own applications



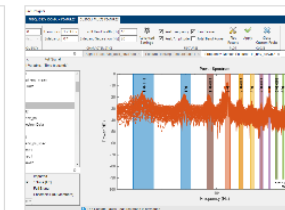
Multi-Class Fault Detection Using Simulated Data

Use a Simulink model to generate faulty and healthy data, and use the data to develop a multi-class classifier to detect different



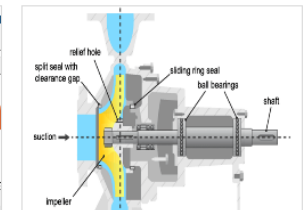
Anomaly Detection in Industrial Machinery Using Three-Axis Vibration Data

Detect anomalies in industrial-machine vibration data using machine learning and deep learning.



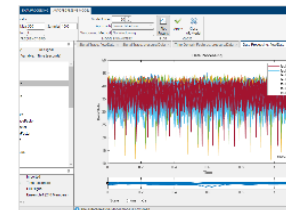
Broken Rotor Fault Detection in AC Induction Motors Using Vibration and...

Use the Diagnostic Feature Designer app to detect broken rotor faults in AC induction motors using vibration and electrical signals.



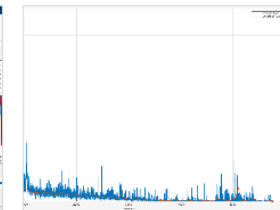
Fault Diagnosis of Centrifugal Pumps Using Steady State Experiments

Use a model-based approach for detection and diagnosis of different types of faults in a pumping system.



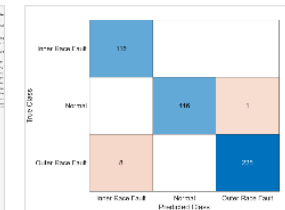
Analyze and Select Features for Pump Diagnostics

Use the Diagnostic Feature Designer app to analyze and select features to diagnose faults in a triplex reciprocating pump.



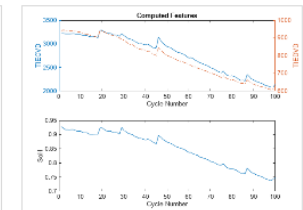
Chemical Process Fault Detection Using Deep Learning

Use simulation data to train a neural network that can detect faults in a chemical process.



Rolling Element Bearing Fault Diagnosis Using Deep Learning

Perform fault diagnosis of a rolling element bearing using a deep learning approach.



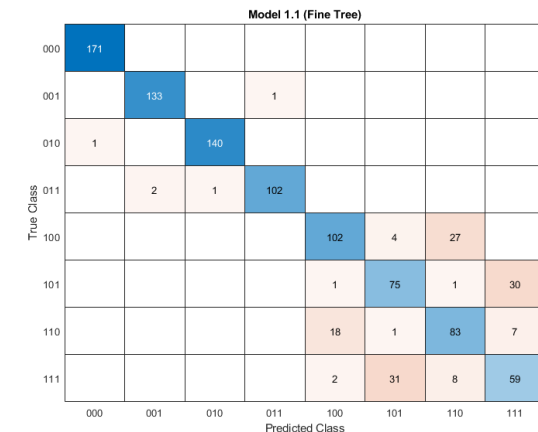
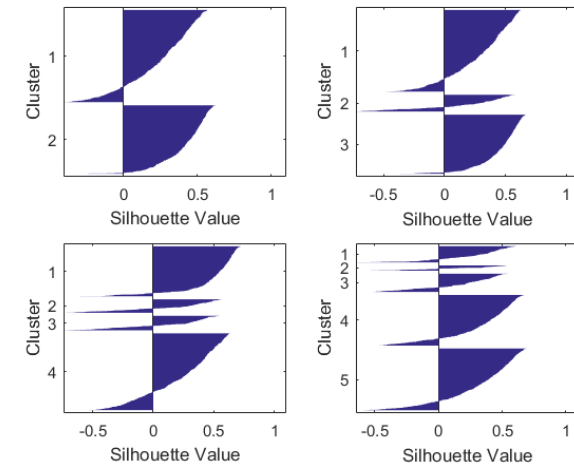
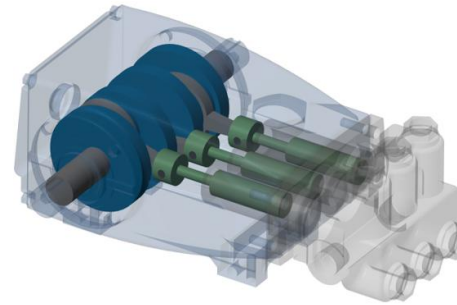
Battery Second-life Application State of Health (SoH) Estimation of Li-ion...

Estimate battery state of health (SoH) for second-life application using measurements from first life and terminal voltage during second

Training Course: *Predictive Maintenance with MATLAB*

Topics included in this 2-day course:

- Importing and organizing data
- Creating custom visualizations
- Fault Detection/Classification
- Preprocessing to improve data quality, and extract time and frequency domain features
- Estimating Remaining Useful Life (RUL)
- Interactive workflows with apps



[See detailed course outline](#)



Achieve Results Faster with MathWorks Predictive Maintenance Experts

Our experts can help your team with the entire predictive maintenance workflow:
Data Preprocessing, Exploratory Analysis, Predictive Modeling, and Operational Deployment



Transparent Approach

You will have full access to all our work throughout your project. Your self-sufficiency is our goal.



Customized Engagements

We'll work with you on a customized project plan aligned to your business goals.



Return on Investment

Reduce development time and cost, learn faster, and improve quality and collaboration.