Internship Presentation by Kyung Ah Woo

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Condition-Based-Maintenance of Electrical Motors for INSIGHT (Intelligent Stennis Gas House Technology) and NPAS (NASA Platform for Autonomous Systems)

December 12, 2019

1. Introduction/ Background

Condition-Based Maintenance vs. Periodic Maintenance

- Condition-Based-Maintenance (CBM) implies that maintenance is done only when conditions indicate that it is necessary
- Periodic maintenance (PM) that is done periodically, whether it is necessary or not.
- PM is more costly than CBM, because the period between maintenance activities needs to be conservative.

	Repair Strategy		
Control Action Type	BRS Breakdown Repair Strate	PMS Preventive Maintenance Strat	CMS Condition based Maintenance Strategy
Technical Maintenance	After failure	Periodic	**Periodic condition based**
Diagnostics		Periodic	Periodic
Medium & Current Repairs	After failure	Periodic	**Condition based**
Overhaul repair	After failure	Periodic	**Condition based**
Breakdown repair	After failure	After failure	After failure

Table 1. Comparative Analysis of BRS, PMS and CMS for Electrical Motor

Goal of this internship: advance CBM capability in NPAS for INSIGHT

2. CBM Definitions

- CBM employs sensor readings as indicators to evaluate if maintenance is needed
  - Probability of Failure (PF) is then calculated based on readings that measure values of parameters that point to maintenance needs
  - Condition indicators – Are values from failure analysis that are used to define alarm settings according to criteria based on analysis of failure progression

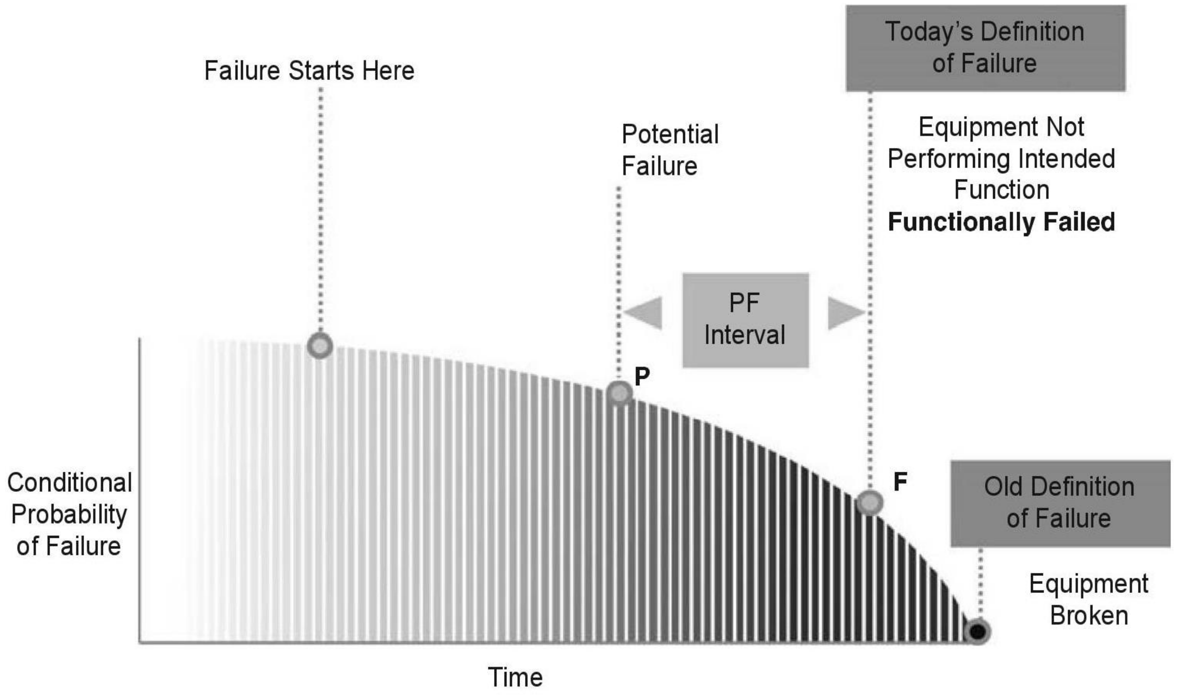


Figure 1. PF curve

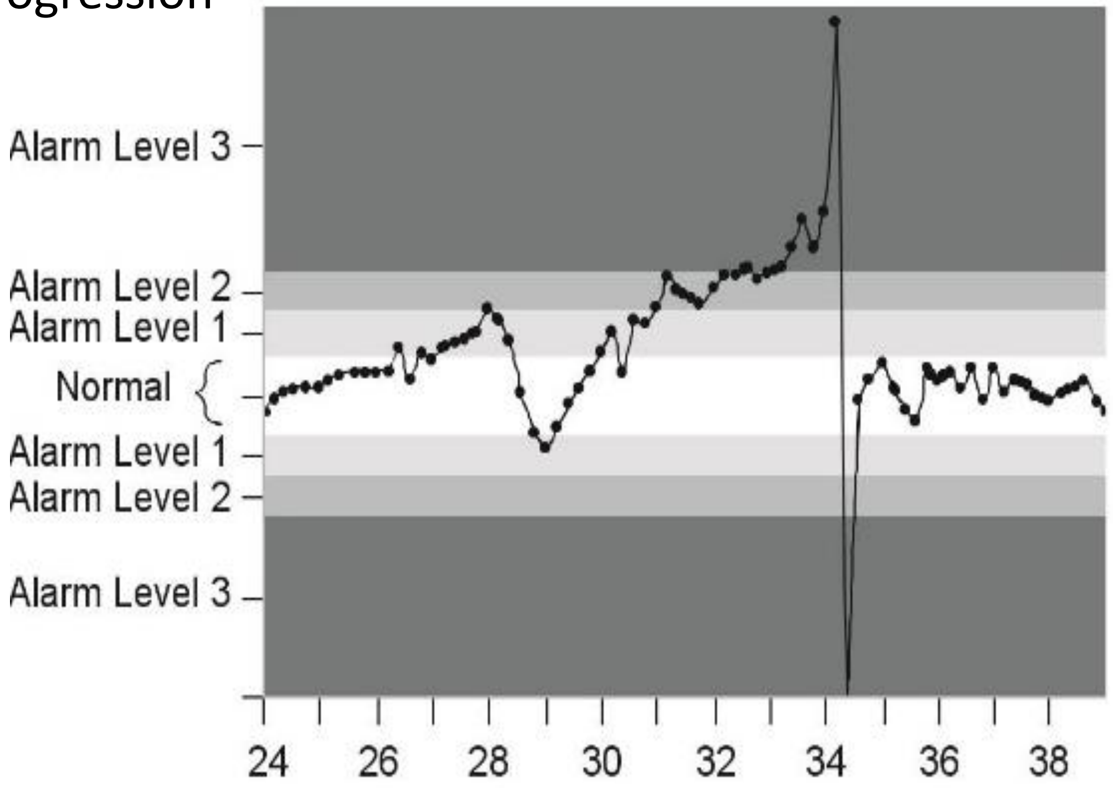


Figure 2. Condition Indicator Graph

3. Common Motor Failures

- Common failures:
  - Bearings (50%)
  - **Stator winding failures (16%)**
  - External environment (16%)
  - Unknown (10%)
  - Rotor bar (5%)
  - Shaft & coupling (2%)`

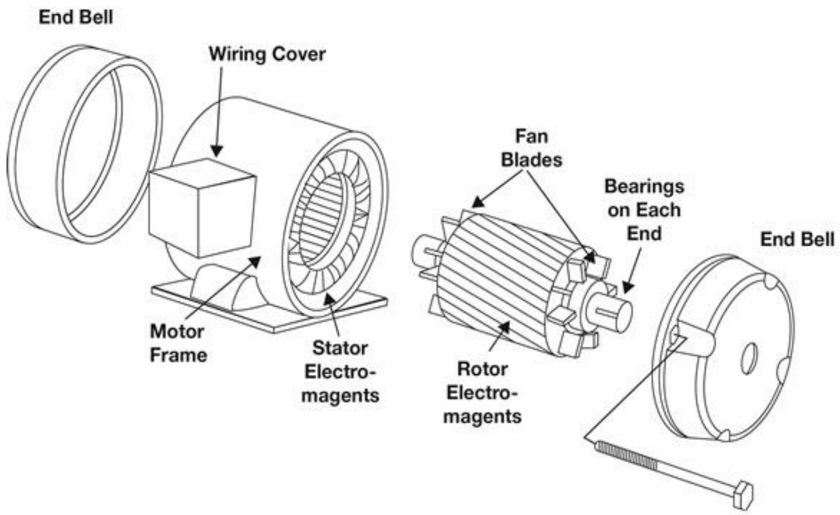


Figure 3. Internal view of a motor

- Examples of bearing failures, include the following:
  - Mechanical failure such as excessive load, overheating,
  - False and true brinelling, normal fatigue failure, reverse loading, contamination, lubricant failure, corrosion, misalignment
  - Loose or tight fits per report from Barden Precision Bearings at Bearing Failure: Causes and Cures

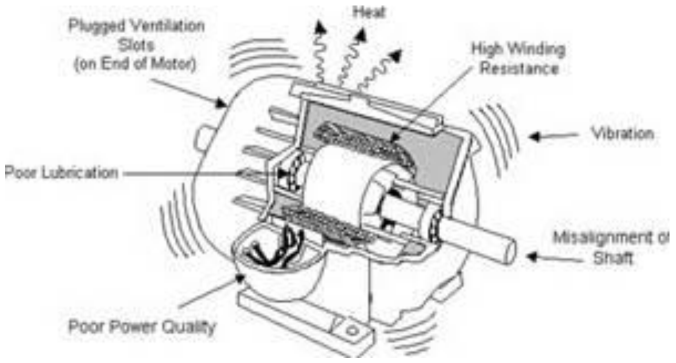


Figure 4. Common Motor Failures

3. Common Motor Failure Indicators

- Three major electrical motor failure indicators include the following:
  1. Electrical overload or over-current
  2. Low resistance
  3. Over-heating
- In order to implement CBM, sensors to measure the above parameters are needed

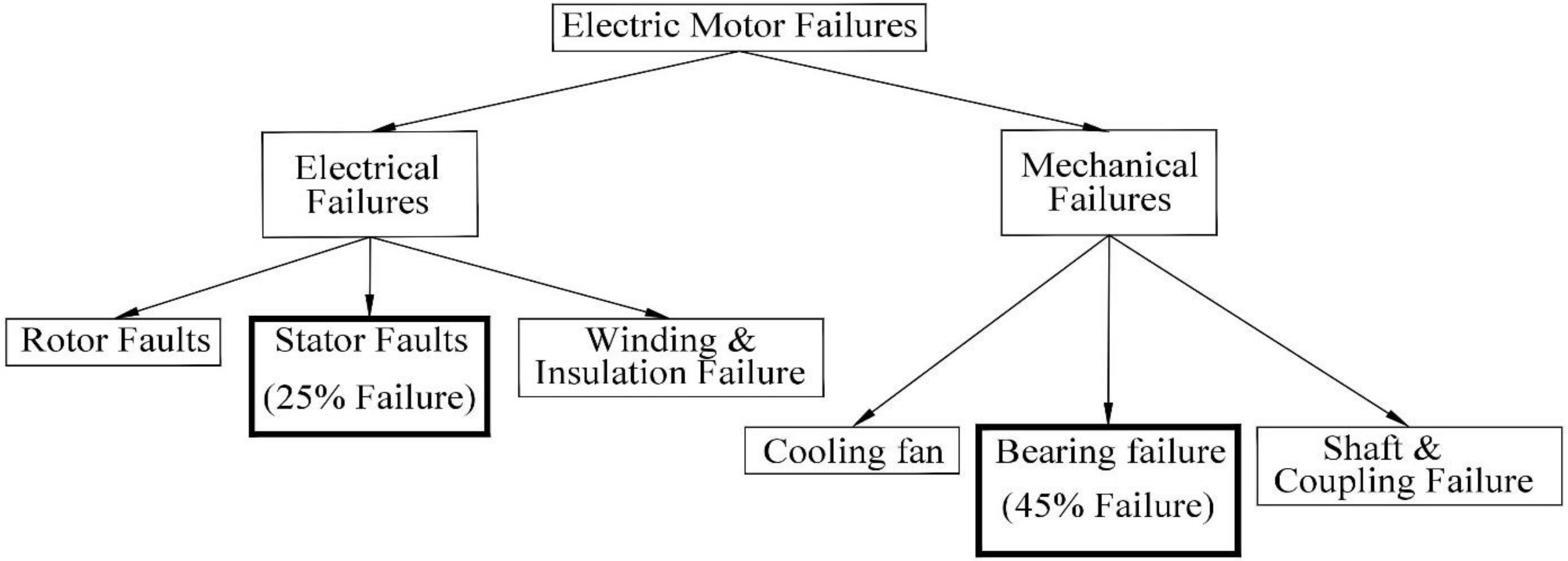


Figure 5. Electric Motor Failures

Motor Failure Can Result from Any of the Following Issues

- **Short cycling:** repeatedly stopping a motor that is already heated to operating temperature, and then starting it again before it has a chance to cool
- **Phase voltage unbalance:** can cause electric motor failure due to an excess temperature rise (in a three-phase supply); ~~A~~ a3% voltage unbalance causes an 18% temperature rise in the motor and current increase of six to ten times the voltage unbalance; a motor should not be operated if the phase unbalance is greater than 5%
- **Physical and environmental conditions**: i.e. restricted ventilation can cause a motor to operate at higher than the desired temperature; improper lubrication can damage bearings and throw grease into windings; moisture, in the form of condensation, can cause rust within a total enclosed motor; vibration can results in motor failures
- **Vibration:** i.e. in the motor, results in unbalance of the rotating element, rubbing parts, loose parts, oil film instabilities; major cause of motor failure
- **High ambient temperatures:** can result in de-rating to a lower horsepower~~.~~

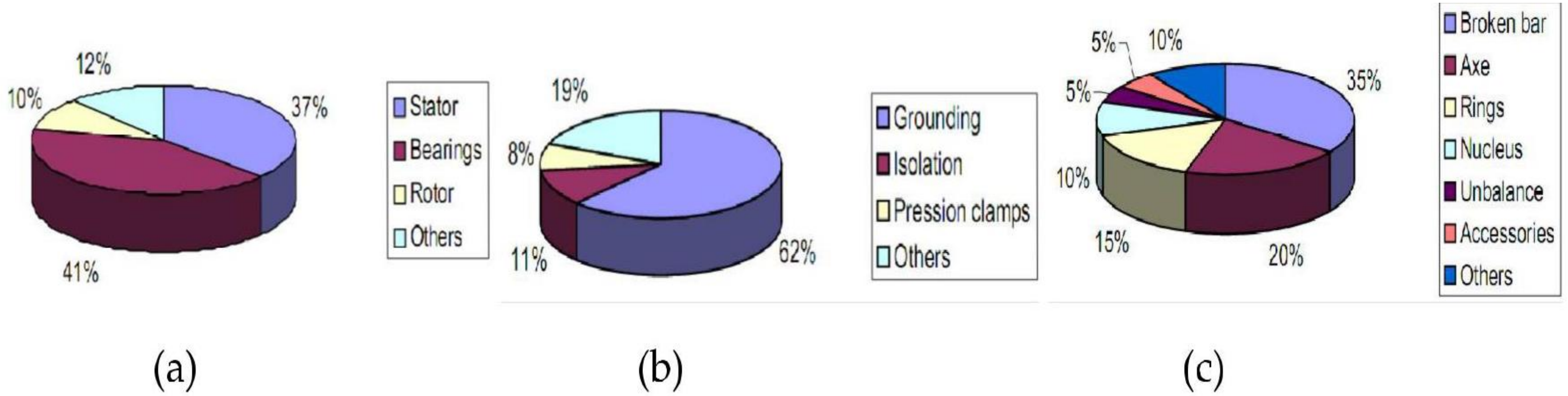


Figure 6. Problems in: (a) Three-Phase Induction Motors, (b) Motor Stator, and (c) Motor Rotor

4. Example Electrical Motor Failures

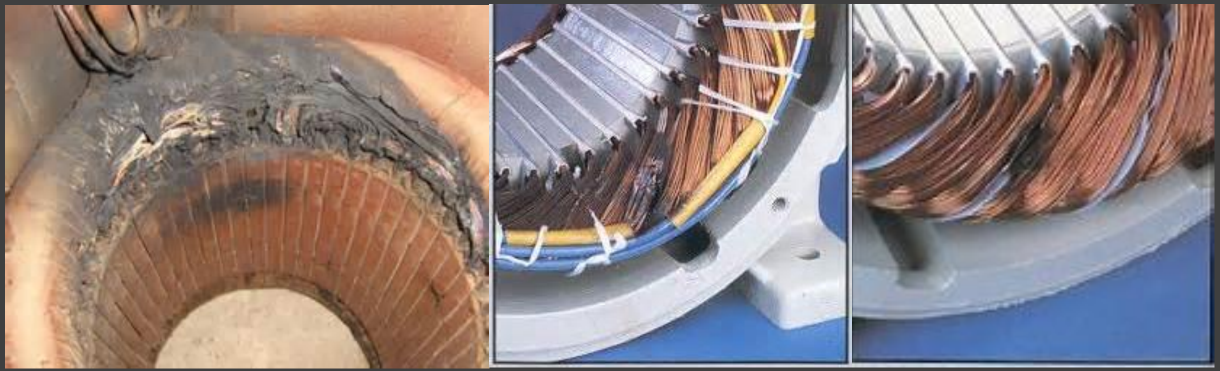


Figure 7. Stator Winding Failure Examples

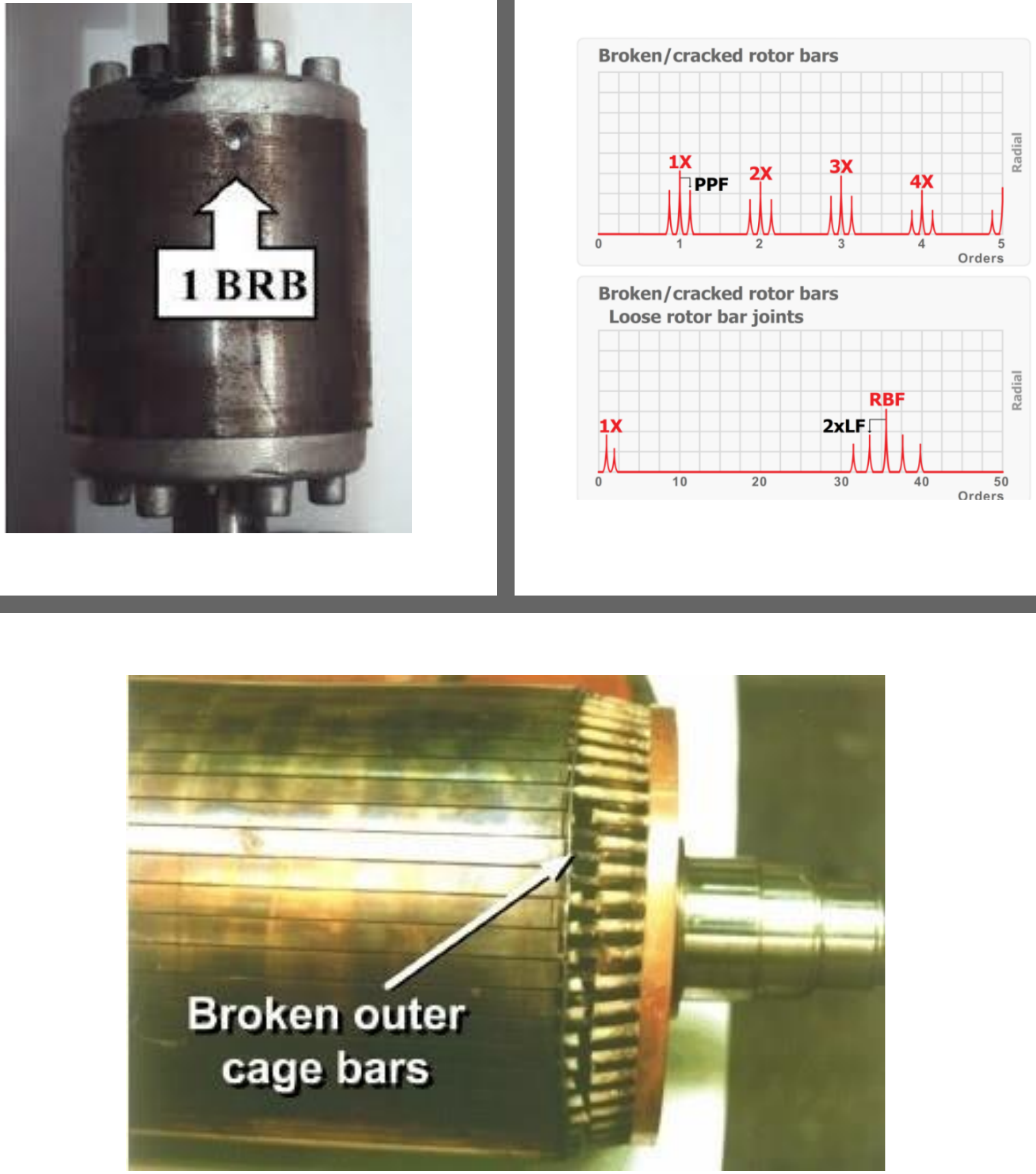


Figure 8. Typical Rotor Problems and Characteristics

5. Description of Sensors Needed for Electrical Motor CBM

Based on Table 2 Technical data, four embedded sensors are proposed:

- (1) Current-Stator and (2) Current-Rotor sensors to detect problems at Stator and Rotor areas
- (3) Thermocouple Sensor for overheating
- (4) Proximity Sensor for monitoring the speed for the Motors

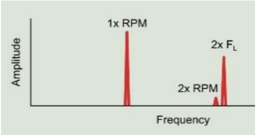
Area Characteristics	Sensor Type	Mech /Elec	Locations	Remedy to fix	Name Model No.	Description
Bearing Frequencies	**Proximity** Vibration Ultrasound	E M P	sleeve or rolling-element bearings	narrowband window to monitor frequencies		*Vibration & Ultrasound sensors will not be included due to focusing on developing electrical CBM system.
Loose rotor bars	**Proximity Current (over-current Protection)** Vibration **Thermo-couple**	E E M P	Stator & Rotor	common failure. High frequency vibration is well above normal max. frequency. High pass filter like high frequency domain for monitoring.	Proximity Switches 608-1	Cylindrical rotor operates at speed between 1500 -3000 rpm Stator eccentricity, stator support weakness or winding shorts 
Imbalance	Proximity Vibration	E M	Entire Motor	narrowband, line frequency indications of Instability	Proximity Switches 608-1	Vibrations in line frequency increase the amplitude of the harmonics of running speed.
Line Frequency	Vibration Ultrasound	P P	Stator & Rotor	For monitoring quality of power		alternating current to the motor. monitor 60, 120, 180-cycle power
Running speed	Proximity Thermo-couple	E P	Stator & Rotor	narrowband WINDOW varies per AC/DC	Proximity Switches 608-1 Thermo C. Probe	
Slip Frequency	Proximity Vibration	E M		narrowband WINDOW	Proximity Switches	is difference bet. Syncro &actual. frequency, modulation, sidebands
Electric Motor analysis						Refer table 2. Technical specifications for motor

Table 2. Specification data for the proposed electrical sensors for the motors

6. Gas House Motor Data Analysis

TO FIND	DIRECT CURRENT	SINGLE PHASE	THREE PHASE
POWER	V x I x EFF	V x I x EFF x PF	1.732 x V x I x EFF x PF
HORSE POWER	V x I x EFF / 746	V x I x EFF x PF / 746	1.732 x V x I x EFF x PF / 746
CURRENT	P / V x EFF	P / V x EFF x PF	P / 1.732 x V x EFF x PF
EFFICIENCY	746 x HP / V x I	746 x HP / V x I x PF	746 x HP / 1.732 x V x I x PF
POWER FACTOR	------	Input Watts / V x I	Input Watts / 1.732 x V x I
SHAFT SPEED	------	------	120 x F / no. of poles

Table 3. Motor Formula

Applying the formulas in Table 3

- I (Current) = 111.9 x 1000 x 746/746) / (460x1.73x.95) = 148.87 Amps when the load from pump is 115.1 KW, Voltage is 460 V, power factor is 95% from the table 4.

	pump	motor
Model	61150-1	Siemens
power (HP)	150/154.3	150
power (KW)	111.9/115.1	111.9
volts (V)	460	460
Frequency (Hz)	60	60
Phase	3	3
mech eff (%)	90	95
SF	1.15	1.15
speed (rpm)		1800/1785
Insulation class		F
design		B
kVA code		G
amps		170
ambient (°C)		40°C
Temp		class B
Weight (lbs)		1720
Frame		B445T
Hrs/day	8	8

Table 4. Nitrogen Reciprocating Pump & Motor Data (nameplate/spec) at HPGH, source: NASA SSC Gashouse, November, 2019

7. Implementation Details: (1) Stator-Current Sensor

- **(1) Stator-Current sensor (SCS):** enables detecting abnormal behavior due to various stresses in stator area.
- Table 5 shows the analysis for CBM

Location	Electrical Failure (Cause)	Governed Formula/ Rule/Graph	Diagnostics/ (Result) Range of Failure	Sensor Type	CBM Warning System Per range of failure
Stator (winding)	Turn-to-turn fault Coil-to-coil fault Phase-to-phase fault from combination of various stresses, electrical, mechanical environmental, and thermal	v(t)= Vpeaks sin(wt) p(t)=v^2(t)/R Ptime aver.= V^2rms/R v(t)=Vpeak sin(wt) i(t)=v(t)/R = Vpeak/R sin(wt) P(t)= v(t)i(t)= (Vpeak)^2/R sin^2(wt)	abnormal current cycle and temperature, Lead to burn	Current (Stator)	Normal Range: $-145<A<+145$ (Green) Alarm Level 1: $-146<A<+165$ (Yellow) Alarm Level 2: $-166<A<+185$ (Orange) Alarm Level 3: (Red) $A>-186$ or $A<+186$

Table 5. Parameter of the Stator-Current sensor (SCS)

7. Implementation Details: (1) Stator Current Sensor

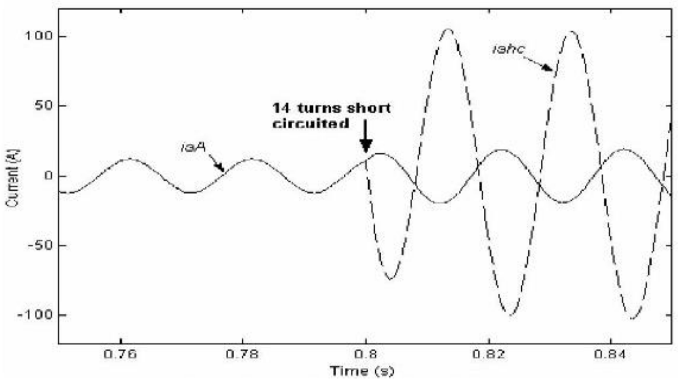


Figure 9. Phase current(isA) and current in short circuited turns

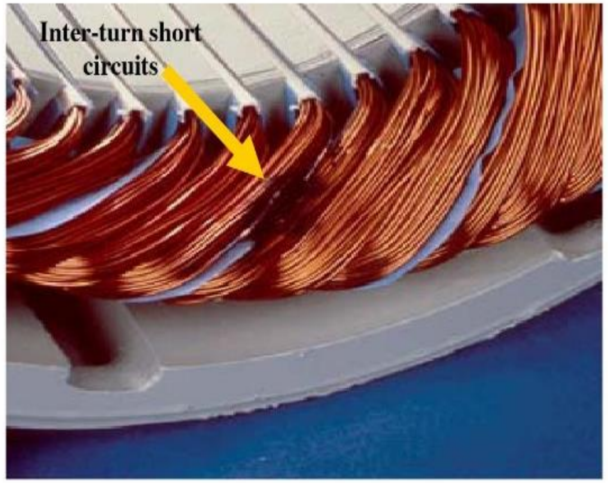


Figure 10. Consequences of inter-turn short-circuit

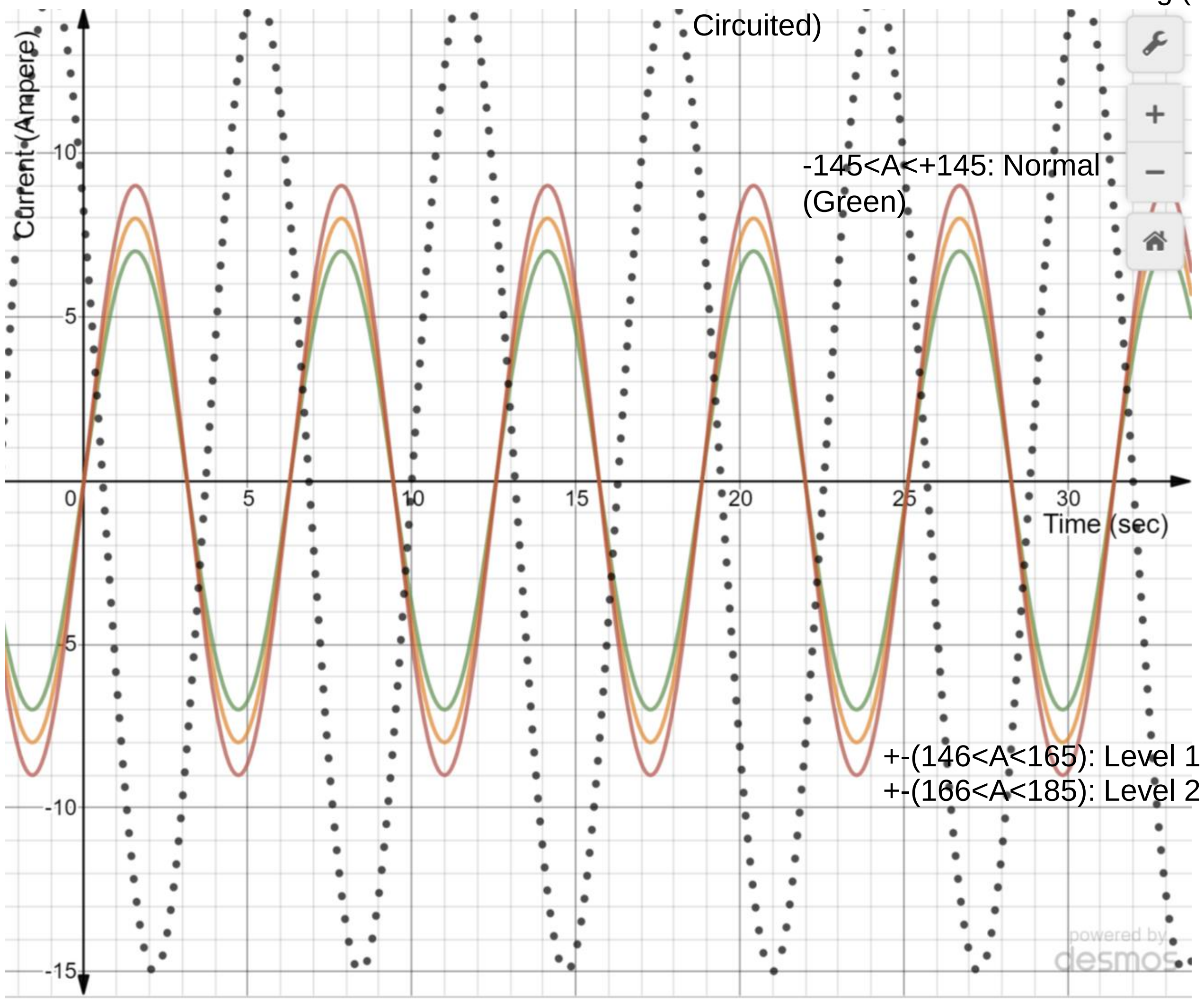


Figure 11. Simulation Data for the Stator-Current sensor

generated by https://www.desmos.com/calculator/t41w64inzb

7. Implementation Details: (2) Rotor-Vibration Sensor

- **(2) Rotor-Vibration sensor (RVS):** Used for detecting abnormal behavior due to various causes in the rotor area.
- Table 6 shows the analysis for CBM

Location	Electrical Failure (Cause)	Governed Formula/ Rule/Graph for 3 Phase AC Motor	Diagnostics/ (Result) Range of Failure	Sensor Type	CBM Warning System Per range of failure
Rotor- Stator (winding)	Cracked or Broken Rotor Bars Eccentricity (uneven airgap bet. Rotor and Stator) Contamination (gunk in the airgap)	Fp=pole pass frequency FL=line frequency PPF = motor slop x no.of poles The difference in amplitude between the FL and FP is an indication of rotor health.	excessive vibration & noise heat & smoke motor failure A difference over 54dB indicates a healthy rotor while less than 45 dB indicates a degraded	Rotor Current	Normal Range -54 < A (Green) Alarm Level 1 -54 > A > -50 (Yellow) Alarm Level 2 -49 > A > -46 (Orange) Alarm Level 3 -45 > A (red)

Table 6. Parameter of the Rotor-Vibration sensor (RVS)

7. Implementation Details: (2) Rotation Vibration Sensor

- Vibration frequency analysis depicts two broken rotor bars with high sidebands (see, Fig. 12); difference in amplitude between the FL (line frequency) and the FP (pole pass frequency) is an indication of motor health.
- Fig.13 shows the simulation for RVS

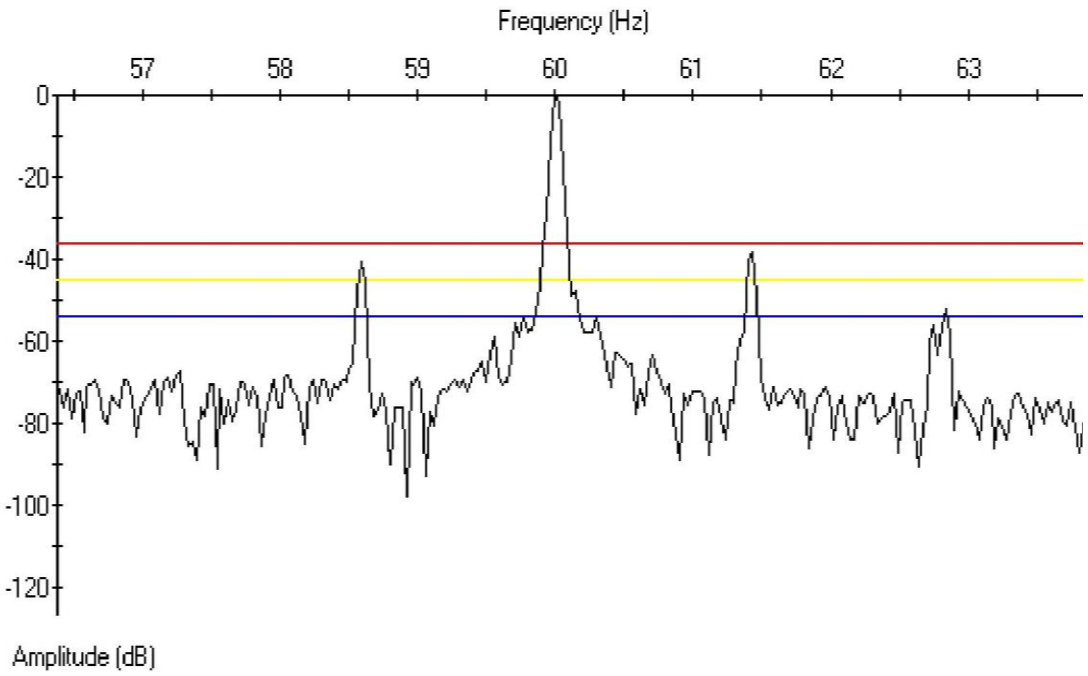


Figure 12. Spectrum of a Motor with Damaged Rotor
source: Pete *Bechard. ADVANCED SPECTRAL ANALYSIS*.
http://masters.donntu.org/2008/eltf/naftulin/library/letter5.htm.

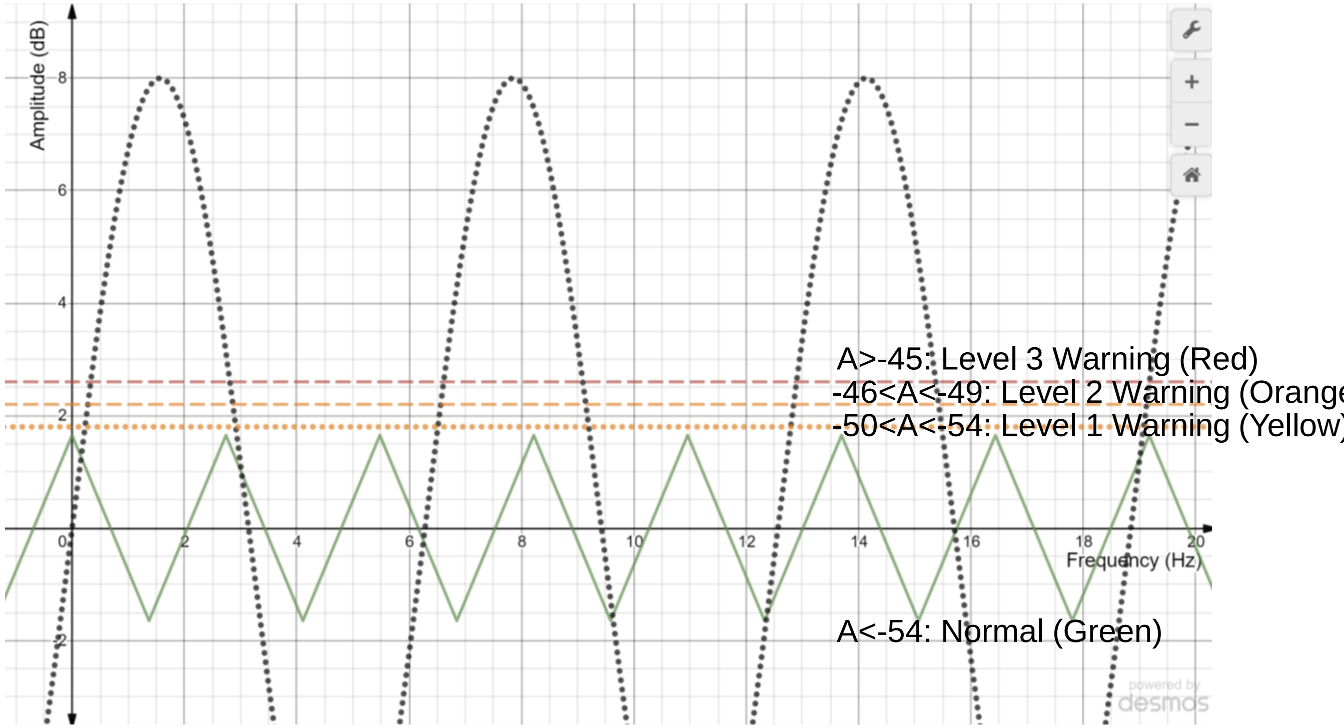


Figure 13. Simulation for the Rotor-Vibration sensor
generated by https://www.desmos.com/calculator/bwegqcu0vt

7. Implementation Details: (3) Thermo Sensor

- **(3) Thermo sensor (TS):** used for detecting exceeding thermal limits in the stator-rotor area.
- Table 7 shows the analysis for CBM.

Location	Failure (Cause)	Governed Formula/ Rule/Graph	Diagnostics/ (Result) Range of Failure	Sensor Type	CBM Warning System Per range of failure
Stator (winding) Rotor Bearings Shaft Frame	Thermal Overload Process Caused (Excessive load) High Ambient Conditions (Hot, Blocked Ventilation) Power Supply Issues (Voltage/Current Unbalance, Harmonics) Phase & Ground fault Over&under Voltage underfrequency Voltage and current Unbalance)	Ieq=sqrt(I2Mx(1+Kx(12/I1)^2) Im= real motor current K=unbalance bias factor I1&I2=positive,negative of motor current K=175/I^2LRC K=230/I^2LRC	Thermal stress causes all the major motor parts failure	Temperature (Thermal Winding Protection)	Normal Range T =< 40 (Green) Alarm Level 1 40 < P =< 155 (Yellow) Alarm Level 2 155 < P =< 165 (Orange) T >= 166 (Red)

Table 7. Parameter of the Thermo sensor (TS)

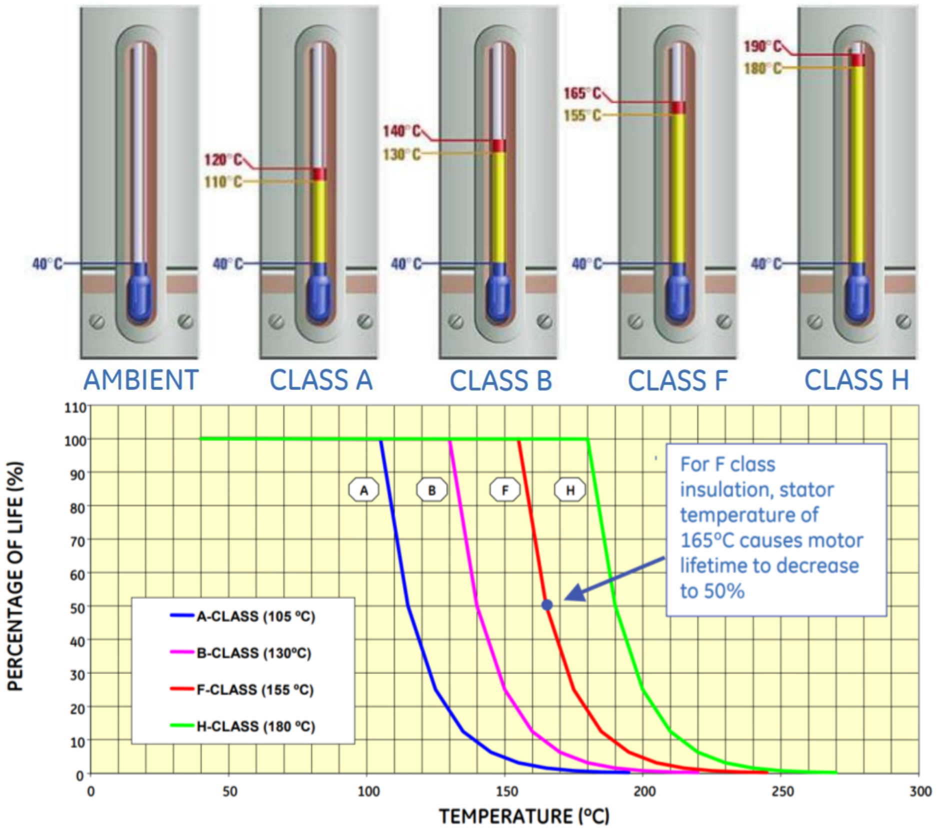


Figure 13. Motor Life-Temperature Curve

Source: SPEED CONTROL OF PMBLDC DRIVE WITH GATE CONTROL METHOD... https://www.researchgate.net/publication/50366358_SPEED_CONTROL_OF_PMBLDC_DRIVE_WITH_GATE_CONTROL_METHOD_USING_CONVENTIONAL_AND_FUZZY_CONTROLLER.

7. Implementation Details: (3) Thermo Sensor

- **(3) Thermo sensor (TS):** ~~is~~ used for detecting abnormal behavior due to various stresses in stator area.
- Table 7 shows the analysis for CBM.

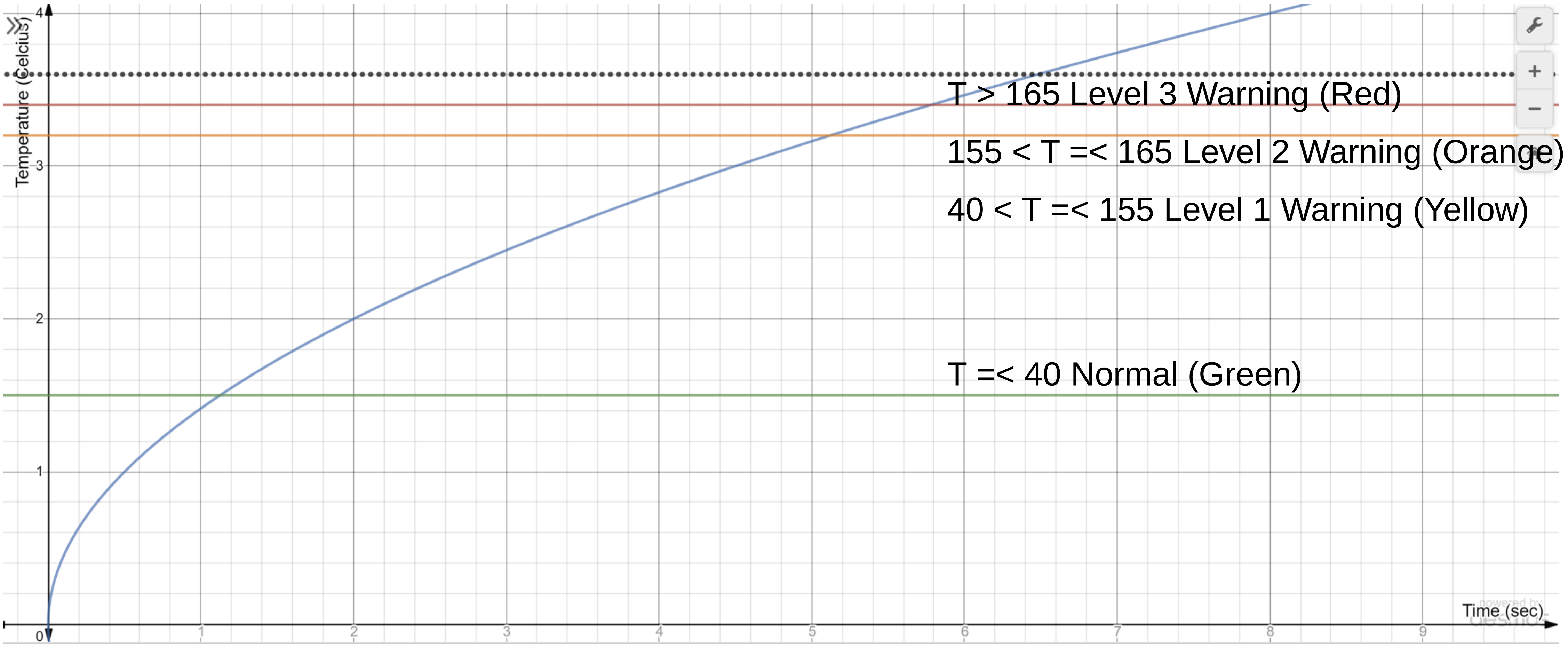


Figure 14. Parameter of the Thermo sensor

7. Implementation Details: (4) Proximity Sensor

- **(4) Proximity Sensor (PS):** ~~is~~ used for detecting abnormal behavior due to various stresses in motor area
- Table 8 shows the analysis for CBM

Location	Electrical Failure (Cause)	Governed Formula/ Rule/Graph	Diagnostics/ (Result) Range of Failure	Sensor Type	CBM Warning System Per range of failure
Stator (winding) Rotor Bearings Shaft Frame	High resistance causes increased losses and reduced efficiency during normal operation. Reasons for slower than rated motor speed Reduced cooling capacity Reduced power efficiency Heat stress	M>=(3xSn) for non-embeddable sensors M= NxdxpixT+(3xSn)/ 60,000 D= Diameter of proximity sensor M=Tooth/gap width (mm) d=Diameter of disc (mm) H= Tooth depth: Axial mounting H>=D Radial mounting 2xSn N= Max. rotational speed or object T= Minimum sensor switching period (1/max.sensor switching frequency) in millisecons [ms] B= thickness of disc Sn/2= Recom. mounting distance	When the mvoltage remains same, an increase in the load (torque) on the motor results in a decrease in speed.	Proximity	Normal Range 1760 < P =< 1800 Alarm Level 1 1672 < P =< 1760 Alarm Level 2 1584 <P =< 1672 Alarm Level 3 1584 >= P

Table 8. Parameter of the Proximity sensor

7. Implementation Details: (4) Proximity Sensor

- **<u>(4) Proximity Sensor (PS):</u>** used for detecting abnormal changes of speed. We can use the formula for the Speed in (rpm) = (120 x Frequency) / No. of Poles. The maximum speed for the PS for 4-pole AC motor is 1,800 rpm.

(120 x 60) / 4 = 1,800 rpm.

Motor Setup:

Poles:	4
HP:	150
Hz:	60
Full Load Amps:	149-170
Standard Range:	1760-1800 rpm (Nameplate RPM is 1,800 rpm)

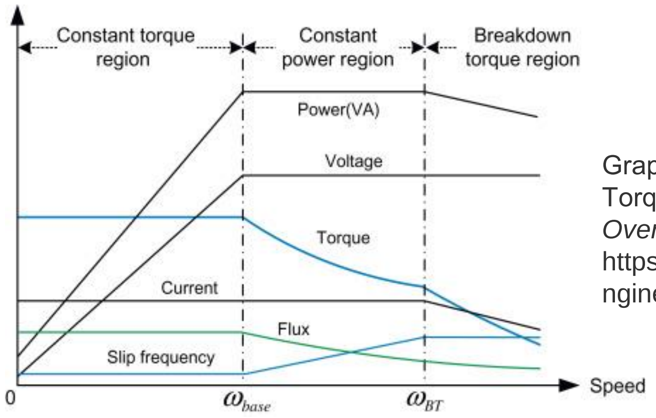
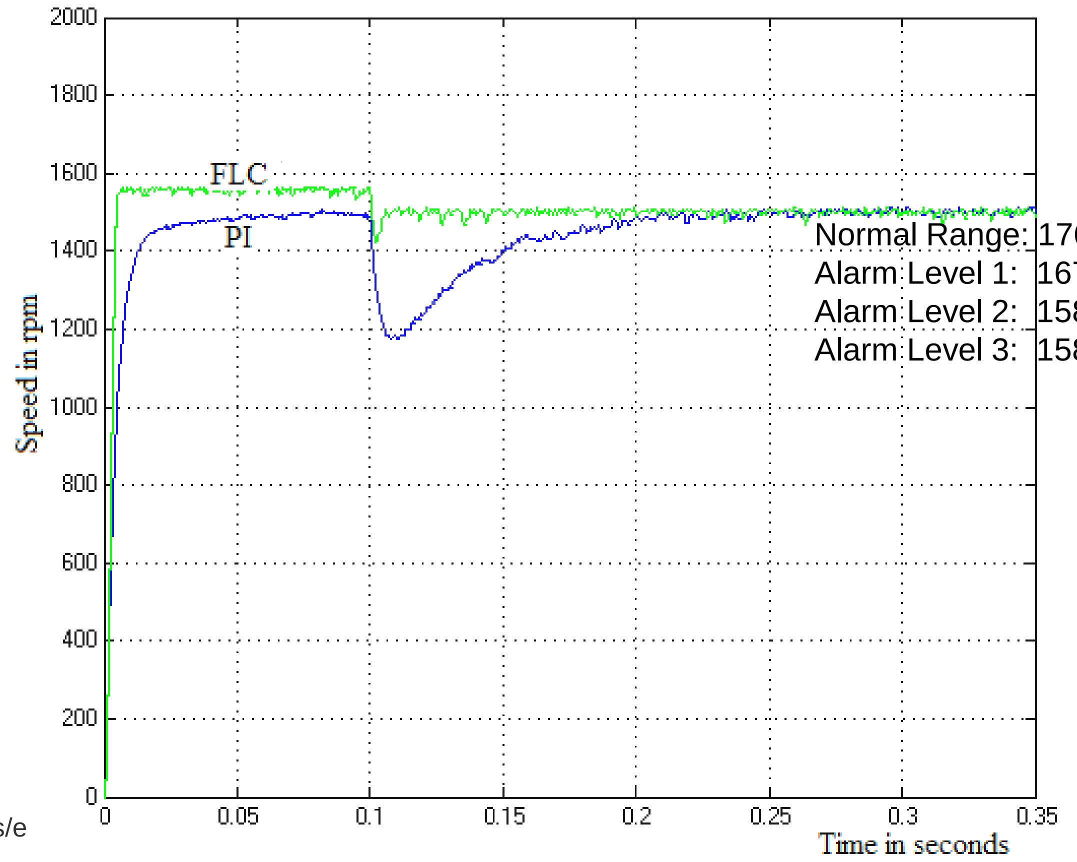


Figure 15. Capability curve of an induction motor

Graph Source: "Breakdown Torque." *Breakdown Torque - an Overview* | *ScienceDirect Topics*, https://www.sciencedirect.com/topics/engineering/breakdown-torque.



Normal Range: 1760<P=<1800
Alarm Level 1: 1672<P=<1760
Alarm Level 2: 1584<P=<1672
Alarm Level 3: 1584>=P

Figure 16. Motor Speed Characteristics

Source: SPEED CONTROL OF PMBLDC DRIVE WITH GATE CONTROL METHOD, https://www.researchgate.net/publication/50366358_SPEED_CONTROL_OF_PMBLDC_DRIVE_WITH_GATE_CONTROL_METHOD_USING_CONVENTIONAL_AND_FUZZY_CONTROLLER

8. G2/NPAS Coding

- Simulation layout for the sensors for the Electrical Systems of small motor-1

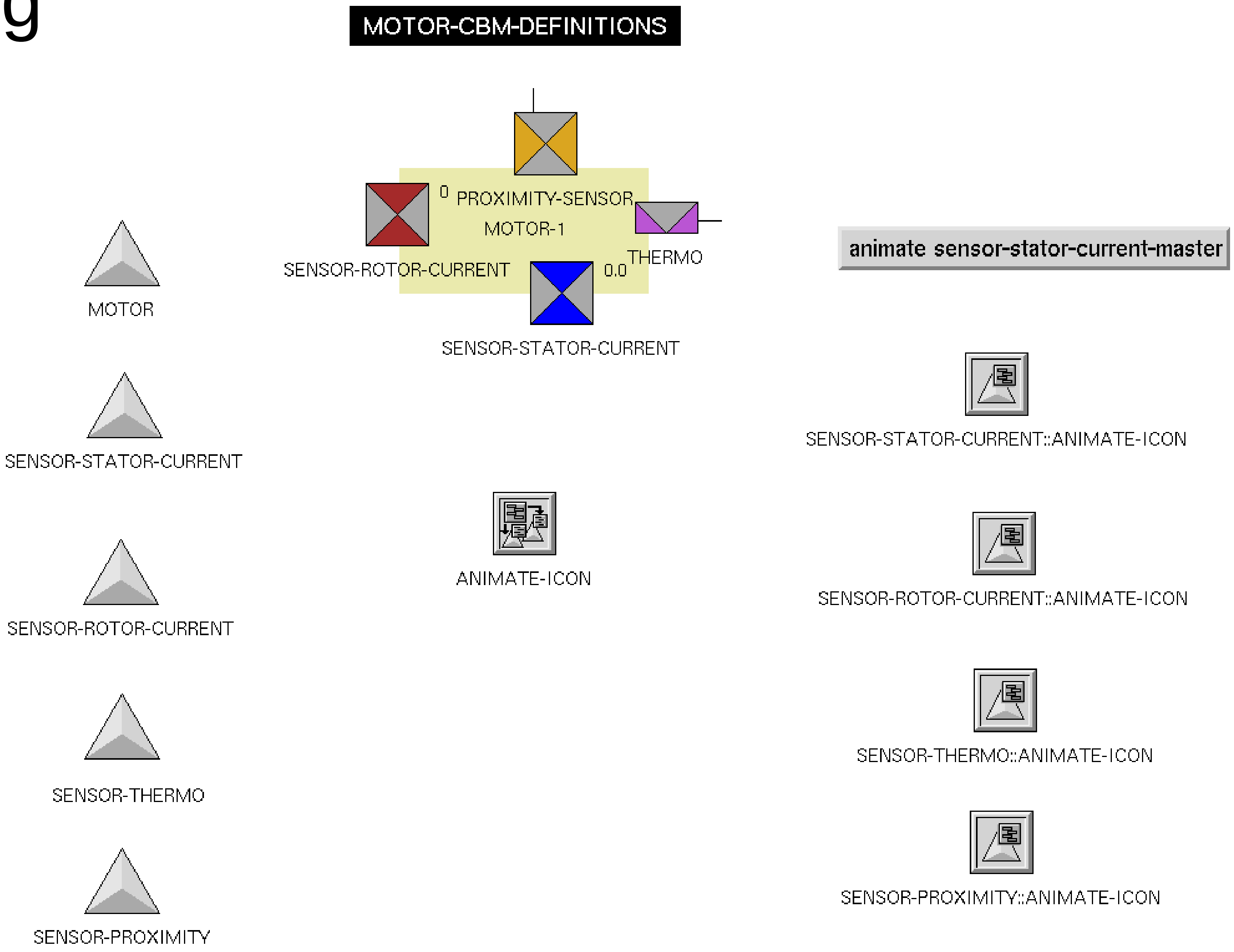


Figure 17. SCS, RVS, TS and PS sensors to the Small Motor-1

8. G2/NPAS Coding for Simulation

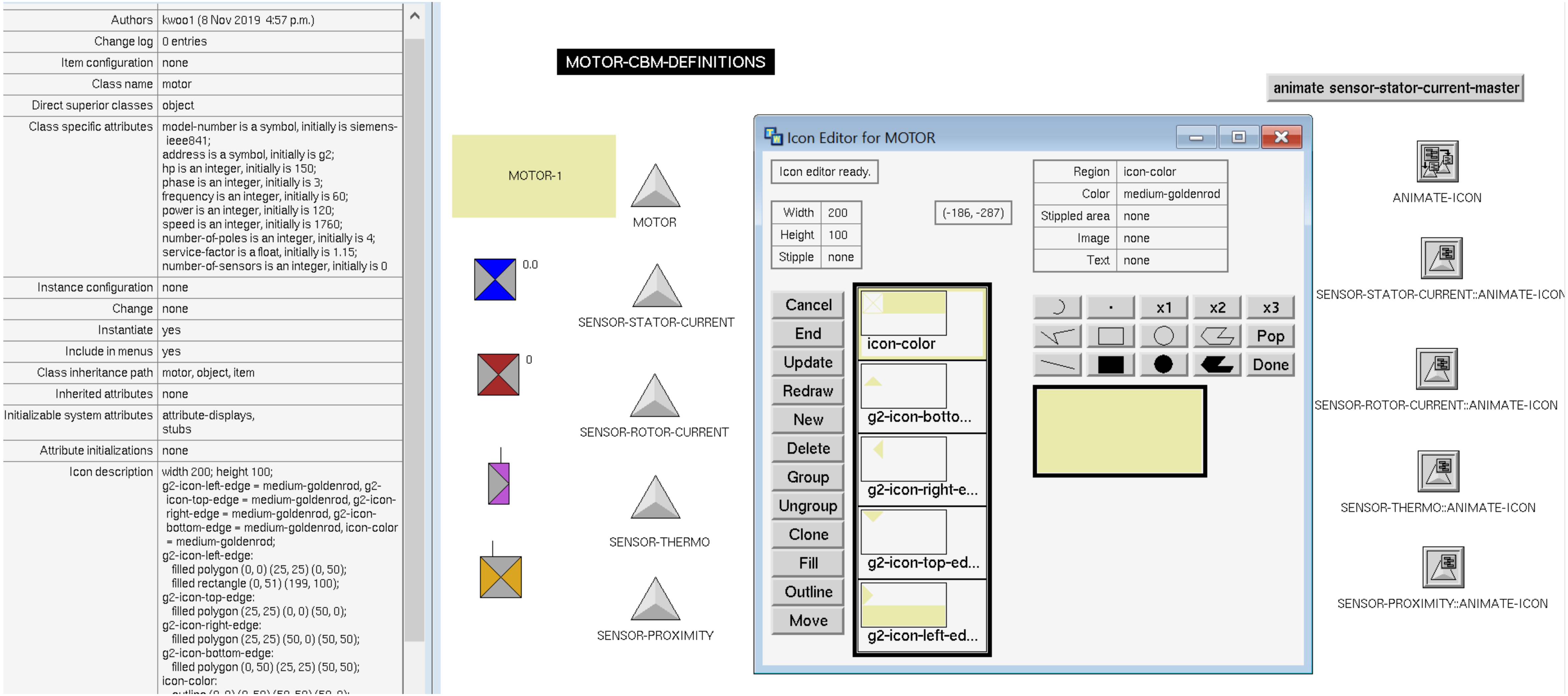


Figure 18. Motor-1 System Layout for the Simulation

8. G2/NPAS Coding: (1) Stator Current Analysis

Notes	OK
Authors	kwoo1 (12 Nov 2019 8:40 p.m.)
Change log	0 entries
Item configuration	none
Class name	sensor-stator-current
Direct superior classes	object
Class specific attributes	address is a symbol, initially is g2; sensor-stator-current is a symbol, initially is s; number-of-sensor-stator-current is an integer, initially is 0; sensor-stator-current-data is a float, initially is 0.0; limit is a float, initially is 185.0
Instance configuration	none
Change	none
Instantiate	yes
Include in menus	yes
Class inheritance path	sensor-stator-current, object, item
Inherited attributes	none
Initializable system attributes	attribute-displays, stubs
Attribute initializations	attribute-displays: sensor-stator-current-data at standard position
Icon description	width 50; height 50; g2-icon-left-edge = gray, g2-icon-top-edge = blue, g2-icon-right-edge = gray, g2-icon-bottom-edge = blue, icon-color = black; g2-icon-left-edge: filled polygon (0, 0) (25, 25) (0, 50); outline (0, 0) (0, 25) (50, 25) (50, 0); g2-icon-top-edge: filled polygon (25, 25) (0, 0) (50, 0); g2-icon-right-edge: filled polygon (25, 25) (50, 0) (50, 50); g2-icon-bottom-edge: filled polygon (0, 50) (25, 25) (50, 50); icon-color: outline (0, 0) (0, 50) (50, 50) (50, 0); lines (0, 50) (50, 0); lines (0, 0) (50, 50)

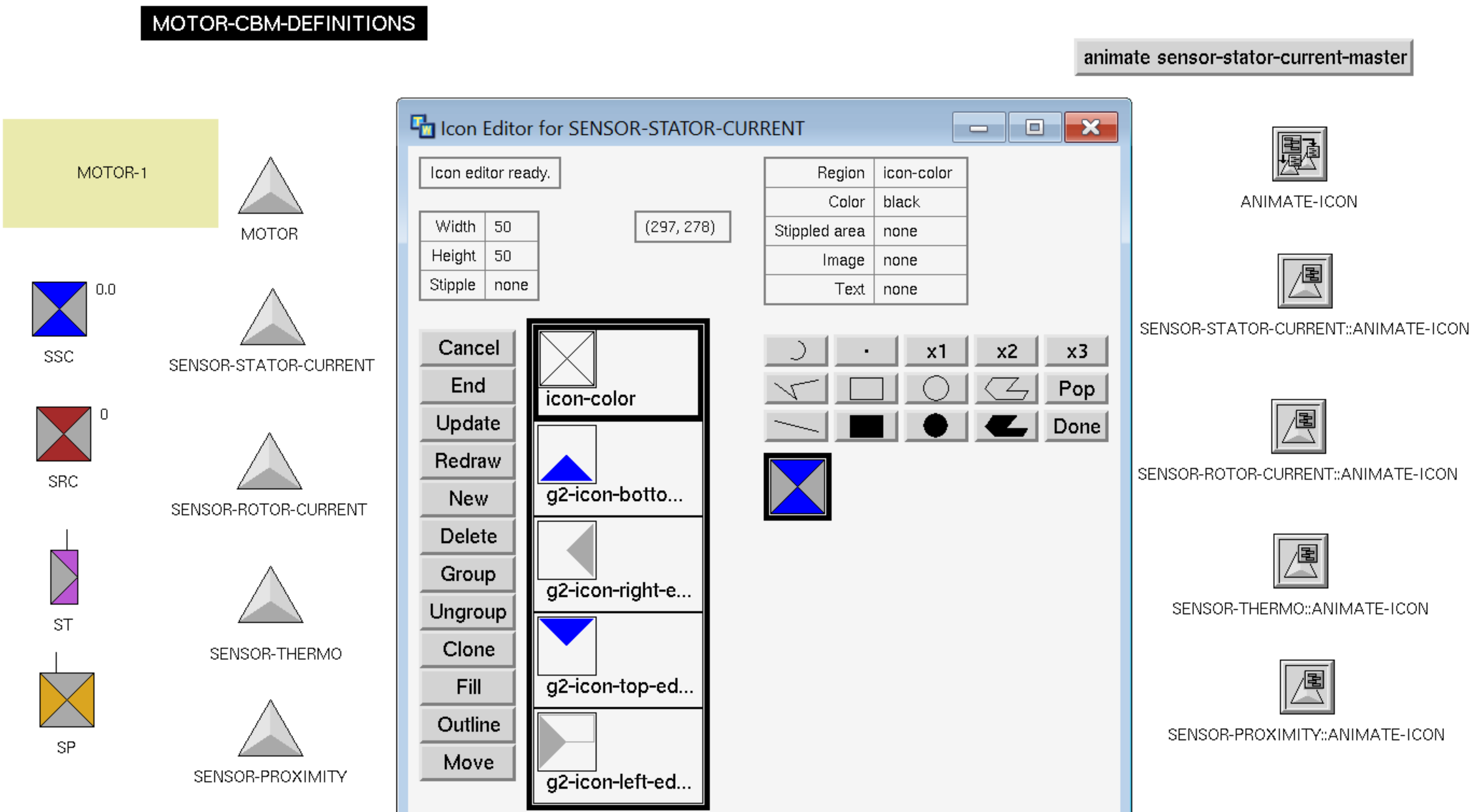


Figure 19. Proposed Stator-Current sensor System

8. G2/NPAS Coding: (2) Rotor Current Analysis

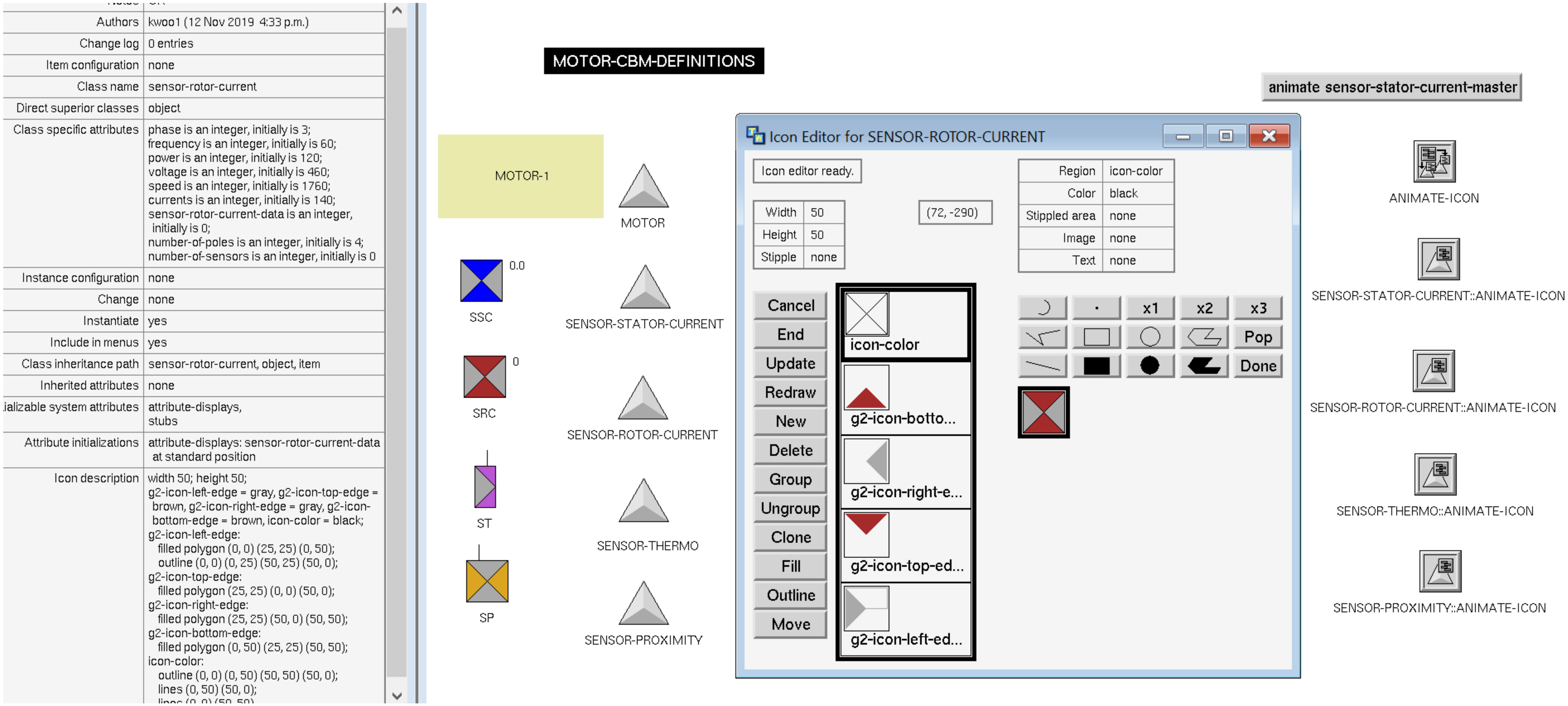
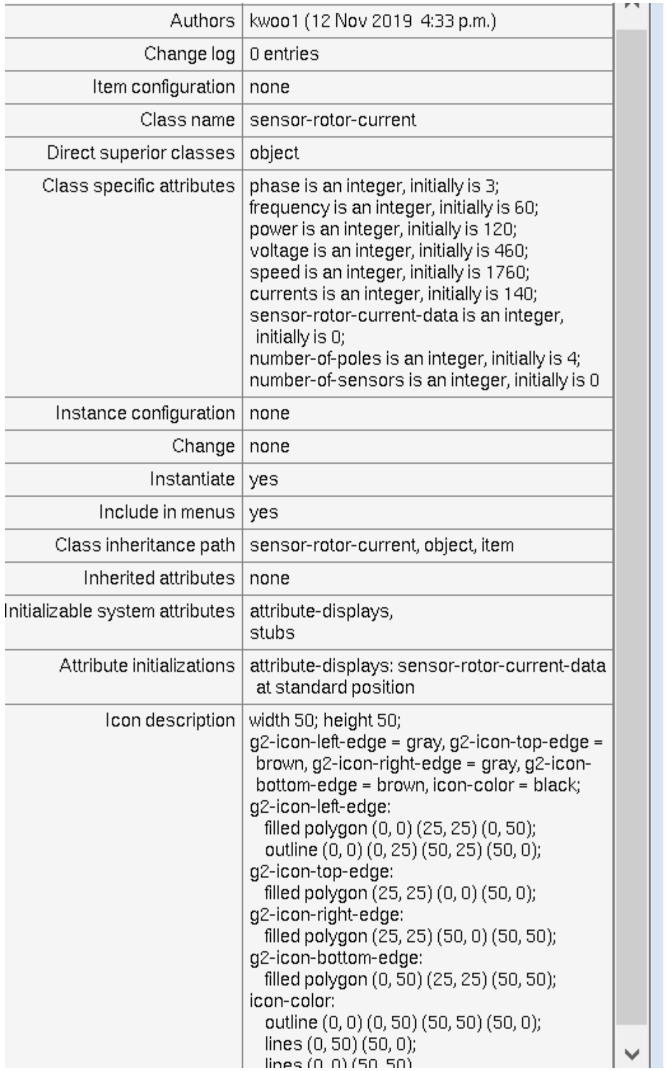


Figure 20. Proposed Rotor-Current sensor System

8. G2/NPAS Coding: (3) Thermo Sensor



Authors	kwoo1 (12 Nov 2019 4:33 p.m.)
Change log	0 entries
Item configuration	none
Class name	sensor-rotor-current
Direct superior classes	object
Class specific attributes	phase is an integer, initially is 3; frequency is an integer, initially is 60; power is an integer, initially is 120; voltage is an integer, initially is 460; speed is an integer, initially is 1760; currents is an integer, initially is 140; sensor-rotor-current-data is an integer, initially is 0; number-of-poles is an integer, initially is 4; number-of-sensors is an integer, initially is 0
Instance configuration	none
Change	none
Instantiate	yes
Include in menus	yes
Class inheritance path	sensor-rotor-current, object, item
Inherited attributes	none
Initializable system attributes	attribute-displays, stubs
Attribute initializations	attribute-displays: sensor-rotor-current-data at standard position
Icon description	width 50; height 50; g2-icon-left-edge = gray, g2-icon-top-edge = brown, g2-icon-right-edge = gray, g2-icon-bottom-edge = brown, icon-color = black; g2-icon-left-edge: filled polygon (0, 0) (25, 25) (0, 50); outline (0, 0) (0, 25) (50, 25) (50, 0); g2-icon-top-edge: filled polygon (25, 25) (0, 0) (50, 0); g2-icon-right-edge: filled polygon (25, 25) (50, 0) (50, 50); g2-icon-bottom-edge: filled polygon (0, 50) (25, 25) (50, 50); icon-color: outline (0, 0) (0, 50) (50, 50) (50, 0); lines (0, 50) (50, 0); lines (0, 0) (50, 50)

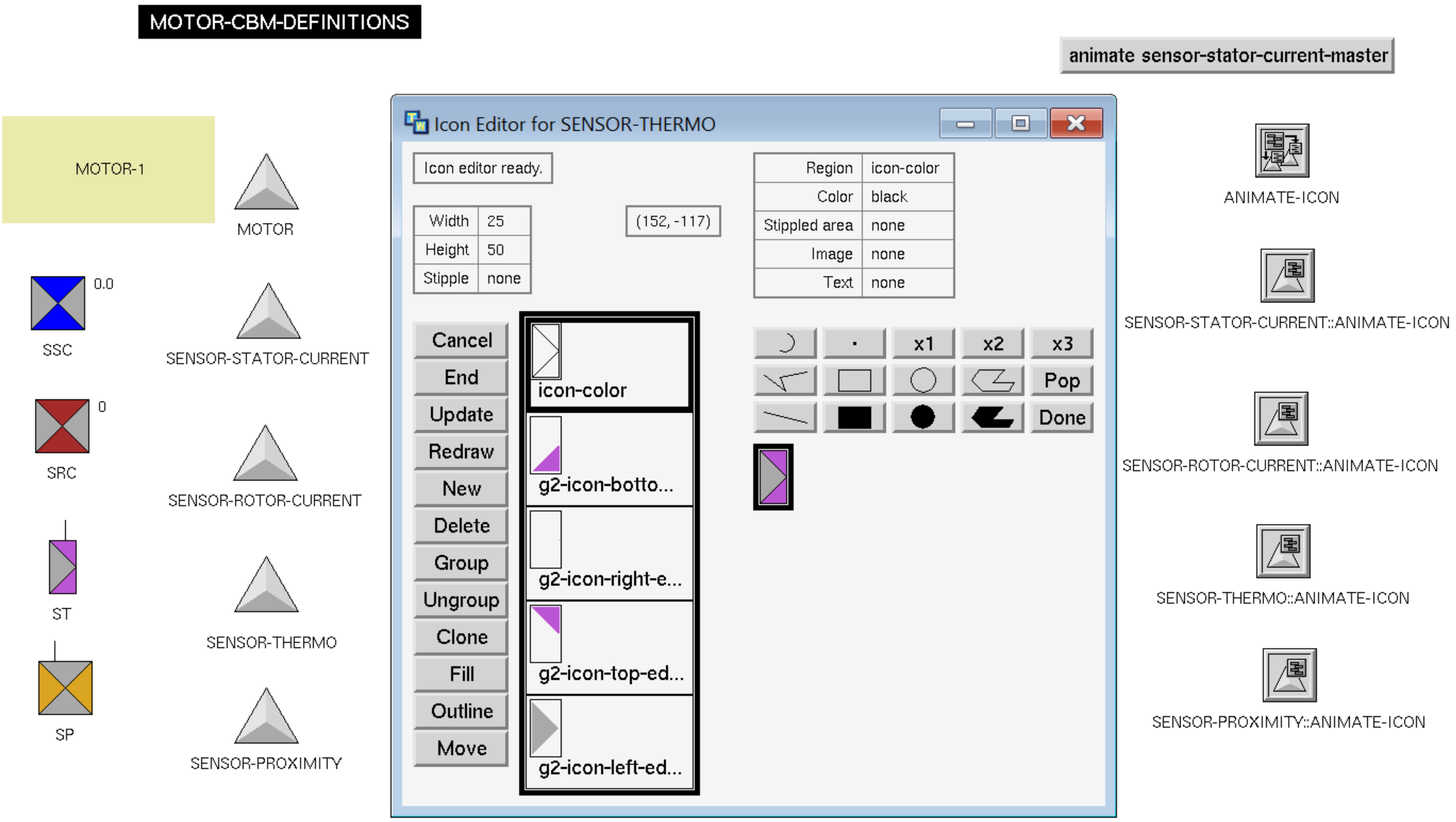


Figure 21. Proposed Thermo sensor System

8. G2/NPAS Coding: (4) Proximity Sensor Analysis

Notes	OK
Authors	kwoo1 (8 Nov 2019 3:05 p.m.)
Change log	0 entries
Item configuration	none
Class name	sensor-proximity
Direct superior classes	object
Class specific attributes	phase is an integer, initially is 3; frequency is an integer, initially is 60; power is an integer, initially is 120; speed is an integer, initially is 1760; number-of-poles is an integer, initially is 4; service-factor is a float, initially is 1.15; number-of-sensors is an integer, initially is 0
Instance configuration	none
Change	none
Instantiate	yes
Include in menus	yes
Class inheritance path	sensor-proximity, object, item
Inherited attributes	none
Initializable system attributes	attribute-displays, stubs
Attribute initializations	stubs: a connection located at top 15 with style diagonal
Icon description	width 50; height 50; g2-icon-left-edge = goldenrod, g2-icon-top-edge = gray, g2-icon-right-edge = goldenrod, g2-icon-bottom-edge = gray, icon-color = black; g2-icon-left-edge: filled polygon (0, 0) (25, 25) (0, 50); g2-icon-top-edge: filled polygon (25, 25) (0, 0) (50, 0); g2-icon-right-edge: filled polygon (25, 25) (50, 0) (50, 50); g2-icon-bottom-edge: filled polygon (0, 50) (25, 25) (50, 50); icon-color: outline (0, 0) (0, 50) (50, 50) (50, 0); lines (0, 50) (50, 0); lines (0, 0) (50, 50)

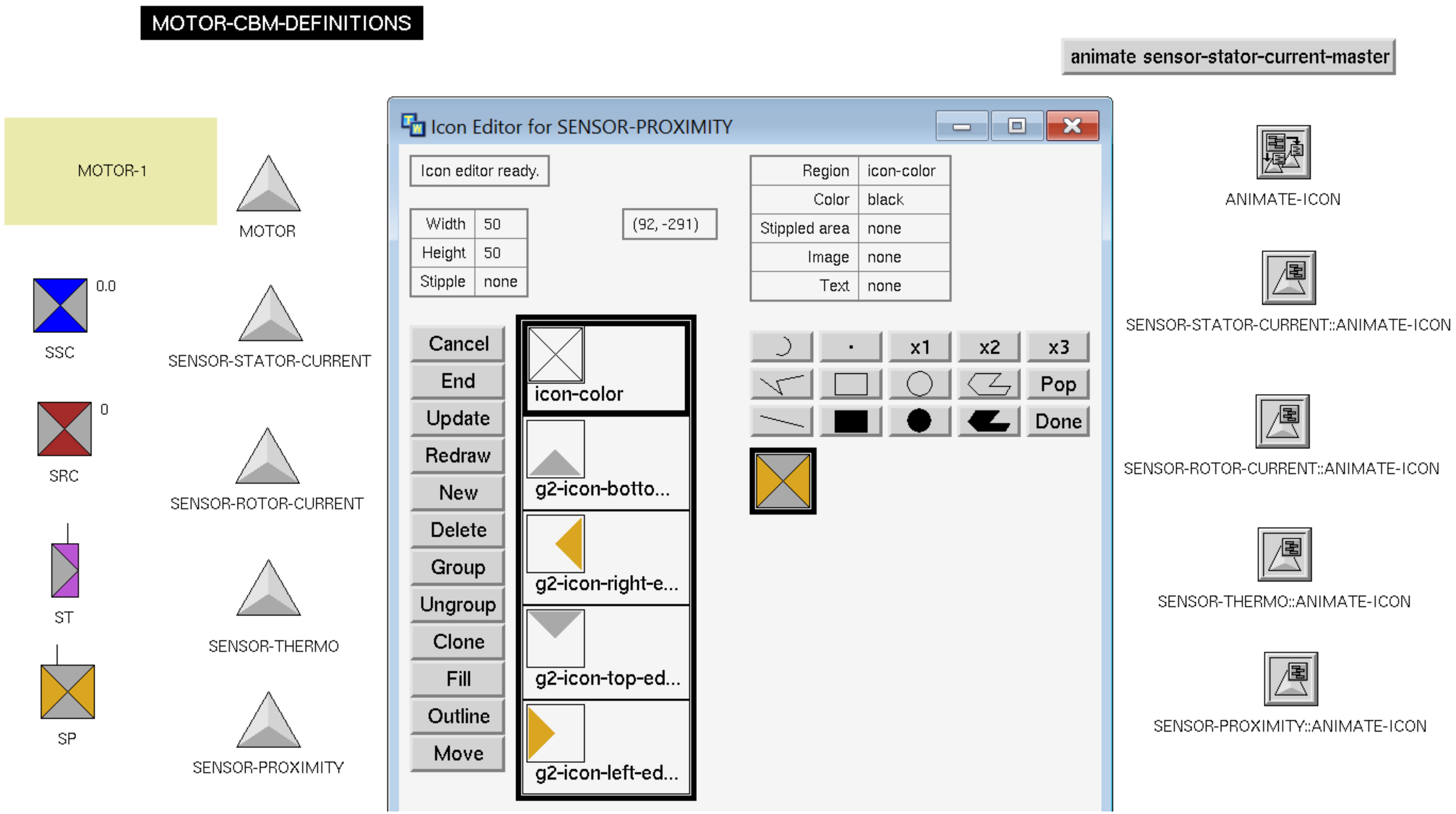
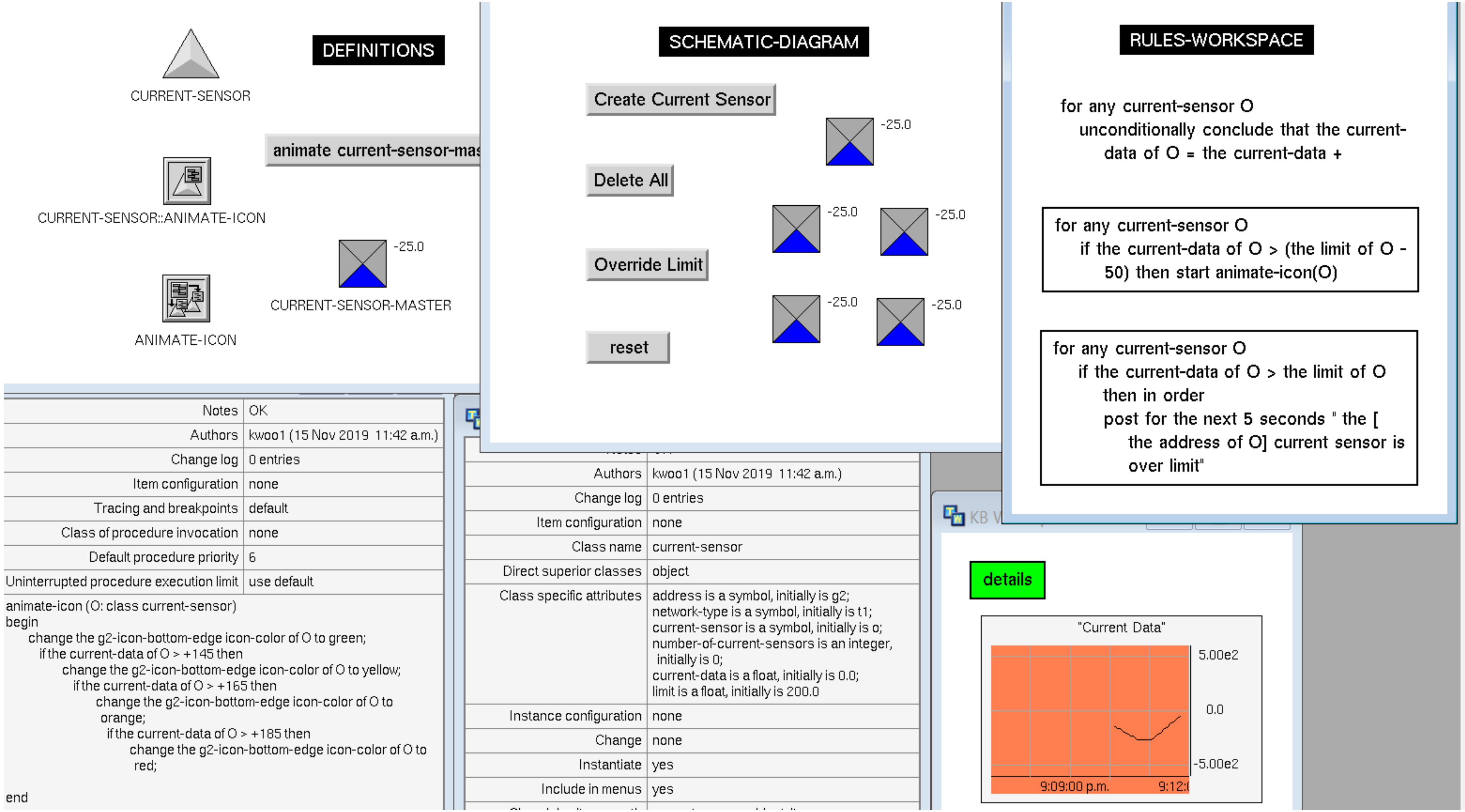


Figure 22. Proposed Proximity sensor System

8. G2/NPAS Coding: Simulation of the Nominal Stator Current



#9 9:05:29 p.m. Resuming running of KB from where it last paused.

#10 9:06:30 p.m. Pause while running KB. You may resume, reset, or restart.

#11 9:08:12 p.m. Resuming running of KB from where it last paused.

#12 9:08:35 p.m. Resetting KB to beginning. You may start when ready.

#13 9:09:05 p.m. Starting to run KB. You may pause, reset, or restart at any time.

#14 9:09:43 p.m. Pause while running KB. You may resume, reset, or restart.

#15 9:10:03 p.m. Resuming running of KB from where it last paused.

Figure 23. Simulation of the Stator-Current sensor in Normal Stage at Motor-1

8. G2/NPAS Coding: Simulation of the Stator Current at Alarm-1

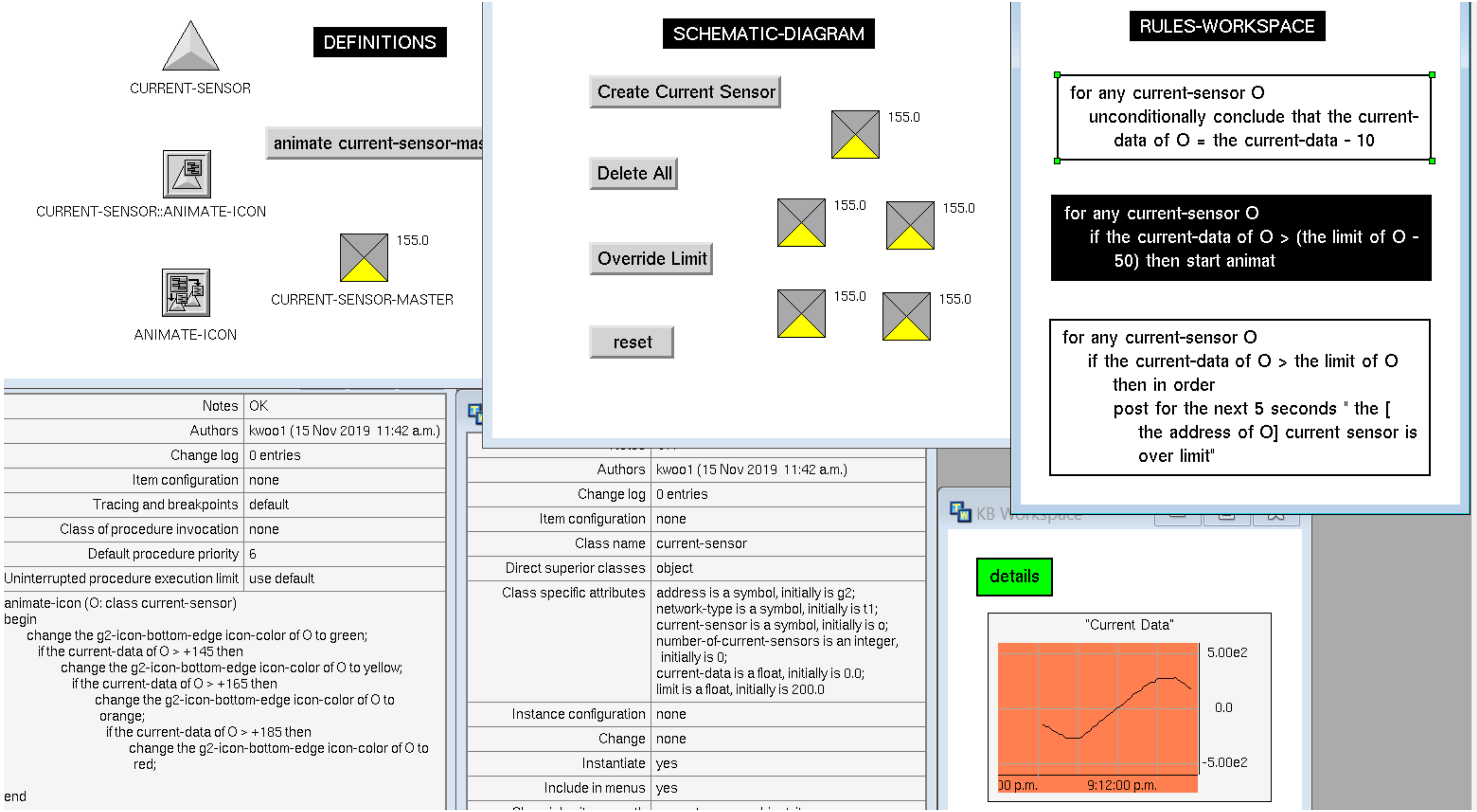


Figure 24. Simulation of the Stator-Current sensor in Alarm Level-1 Stage at Motor-1

8. G2/NPAS Coding: Simulation of the Stator Current at Alarm-2

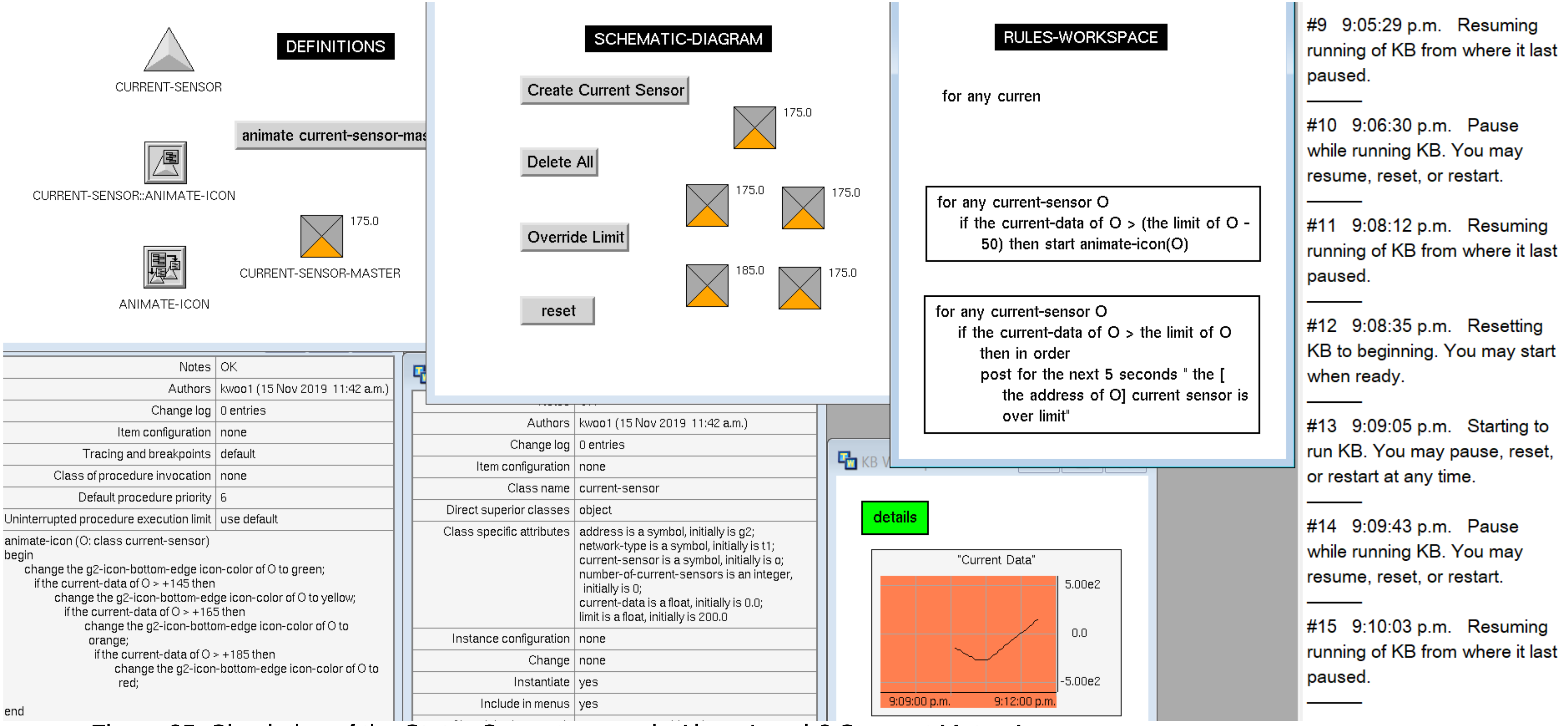


Figure 25. Simulation of the Stator-Current sensor in Alarm Level-2 Stage at Motor-1

8. G2/NPAS Coding: Simulation of the Stator Current at Alarm-3

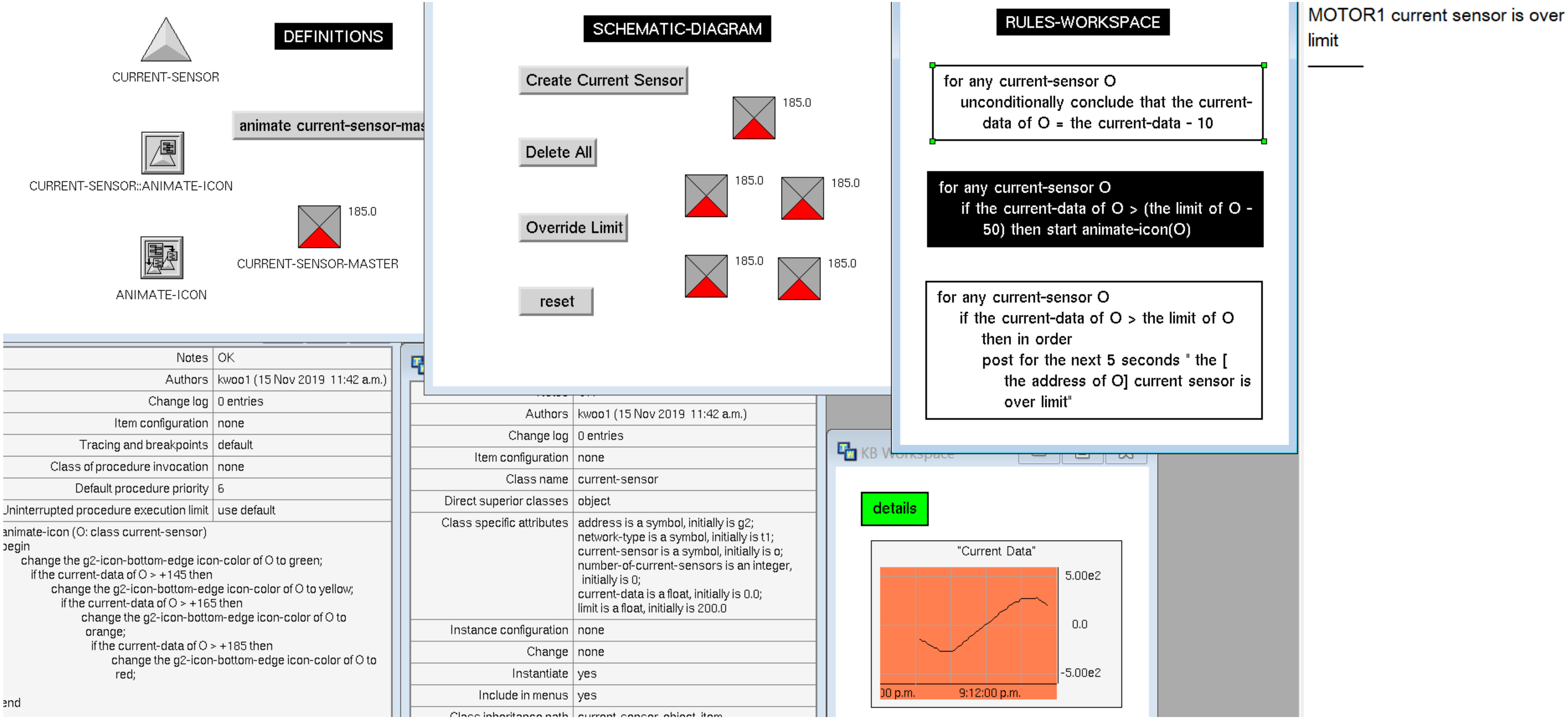


Figure 26. Simulation of the Stator-Current sensor in Alarm Level-3 Stage at Motor-1

8. G2/NPAS Coding: Simulation of the Stator Current Back at Nominal State

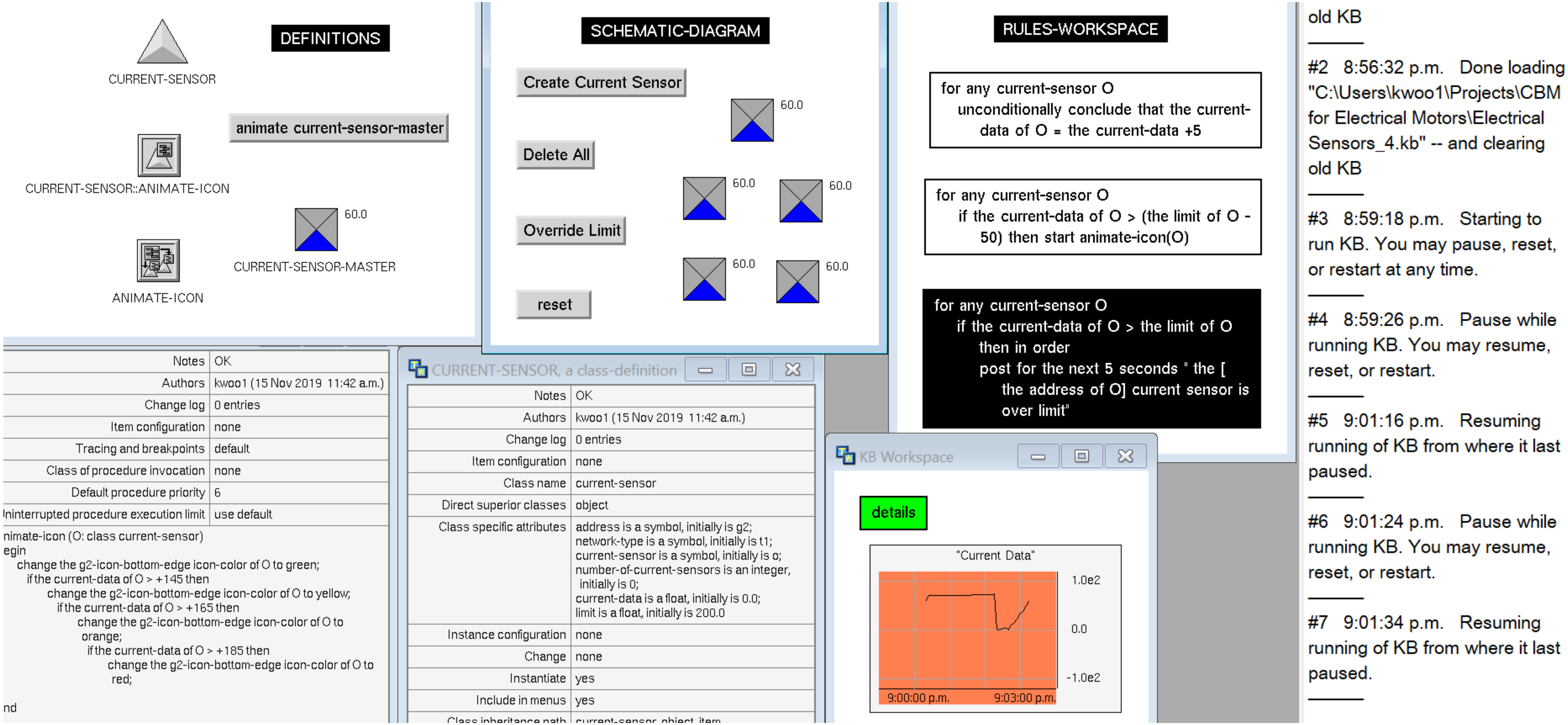


Figure 27. Simulation of the Stator-Current sensor back to Normal Stage at Motor-1

9. Conclusion

- This internship study looked at assessing visual-indicators, sensing needs for condition assessment, as well as an approach for implementation of CBM of electrical motors
- This work also provided the training to initiate preliminary coding in G2/NPAS, and the foundation for future guidance for further research and development of CBM implementation in INSIGHT with G2/NPAS

10. Acknowledgement

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