

# MATLAB EXPO

풍력발전기 예지적 유지보수를 위한  
MATLAB 프로그램의 활용  
*최정철, 한국에너지기술연구원*

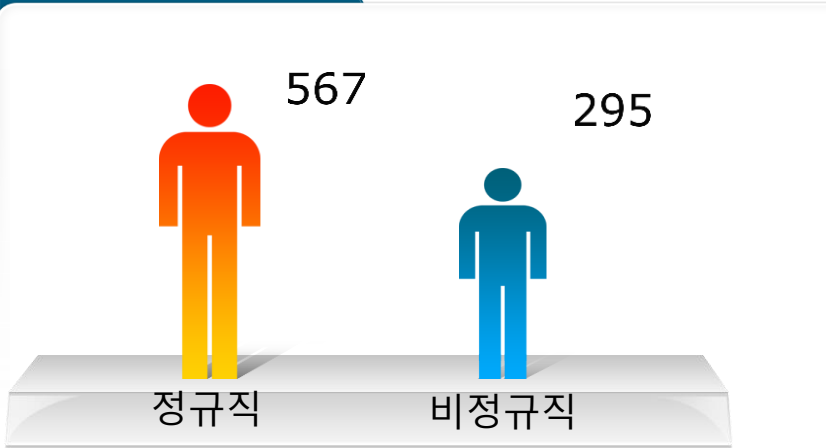


## 목차

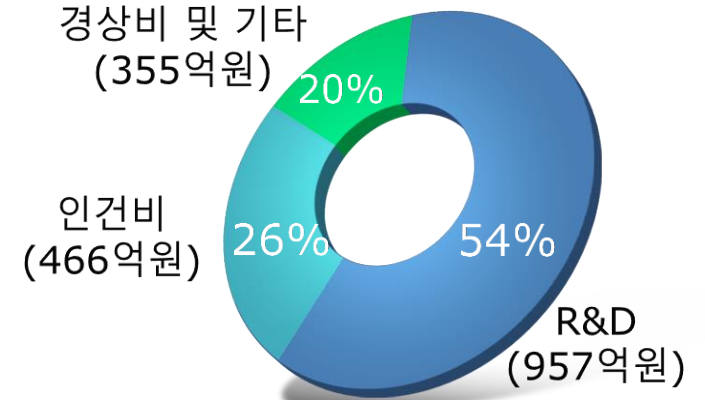
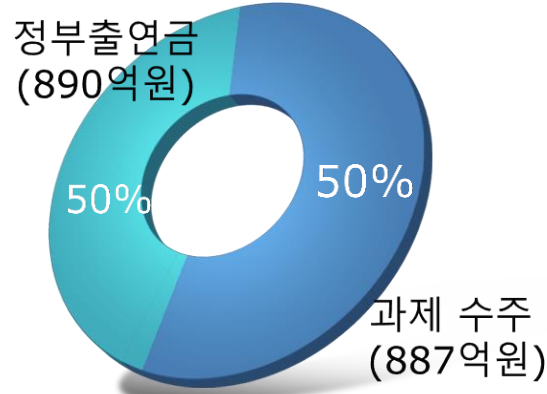
- 회사 및 발표자 약력
- 프로젝트 개요
- 기술적인 해결 과제
- 해결 방안 및 결과 (MATLAB)
- 결과 및 정리
- 다음 과제 (MATLAB)
- 결론

# 1. 회사 및 발표자 약력

## Personnel



## 2019 budget (1777억원)



**01 에너지기술개발**

- 에너지효율향상 연구개발
- 신·재생에너지 연구개발
- 이산화탄소 처리 및 이용 연구개발
- 화석에너지 청정이용 연구개발
- 에너지관련 융·복합 연구개발

**02 에너지기술 보급 확산 및 중소기업 육성**

- 우수 에너지기술의 기술사업화 및 보급 확산
- 중소·중견기업의 역량강화를 위한 공동 기술개발 및 애로기술 지원
- 시험평가, 인증, 인력 양성

**03 에너지기술 정책수립 지원**

- 국내·외 에너지기술 개발 동향 수집, 분석
- 에너지·환경문제 대응 미래 전략기술 기획 및 정책반영 지원

# 1. 회사 및 발표자 약력

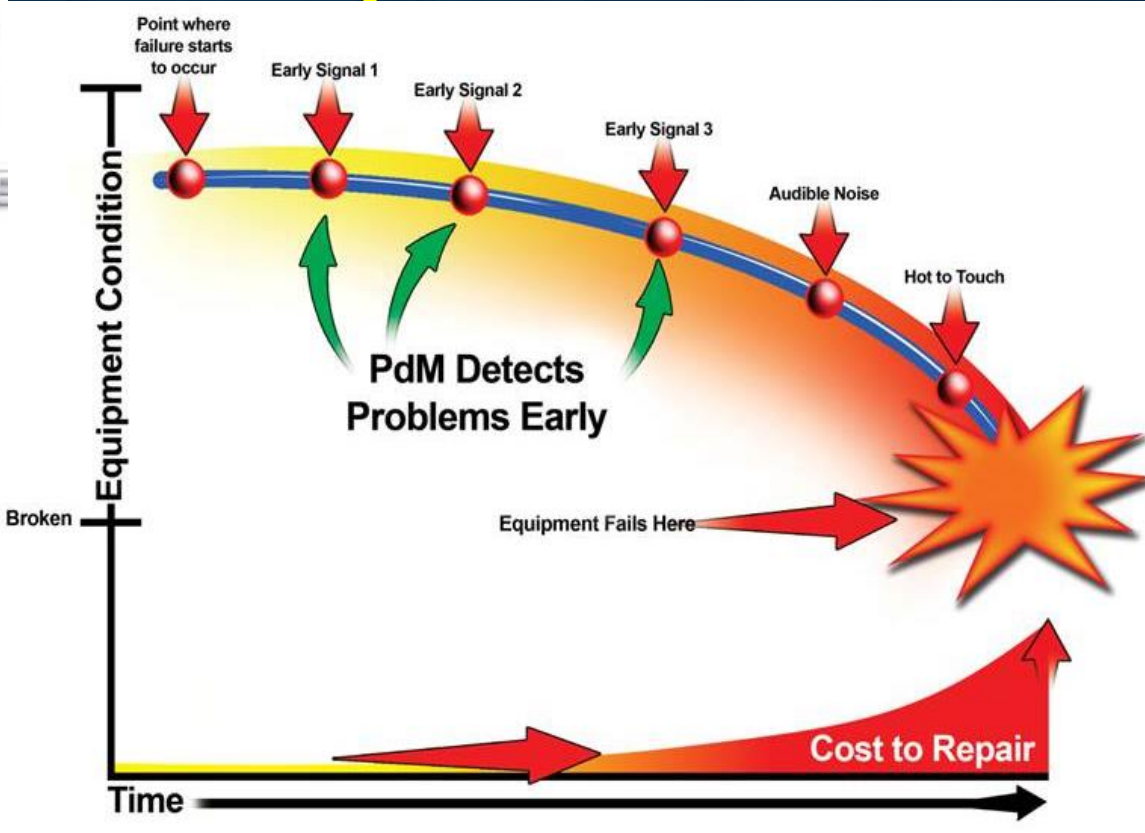
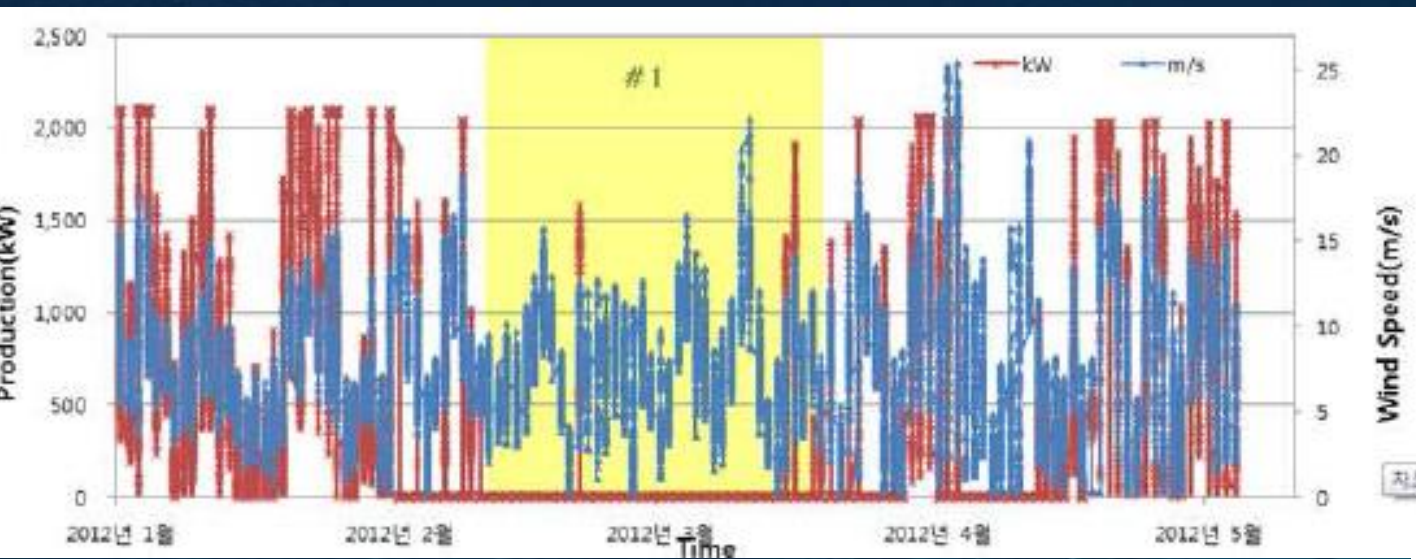
**발표자: 최정철**

한국에너지기술연구원 (현재)  
Fraunhofer 풍력연구소 (독일)  
GE Wind Energy (독일)

TC88 IEC61400-50-3 한국 대표  
IECRE SG551 한국 대표

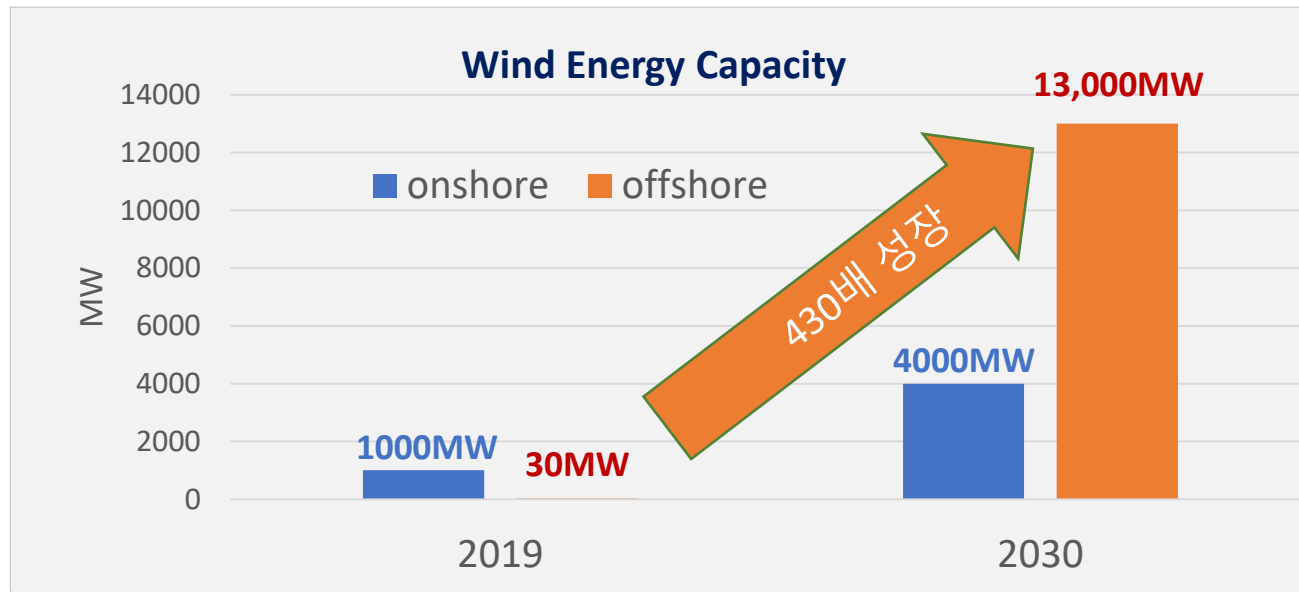
박사: Kassel University (독일)  
석사: Stuttgart University (독일)  
학부: 연세대학교

## 2. 프로젝트 개요






## 2. 프로젝트 개요



## 2. 프로젝트 개요


**onshore**



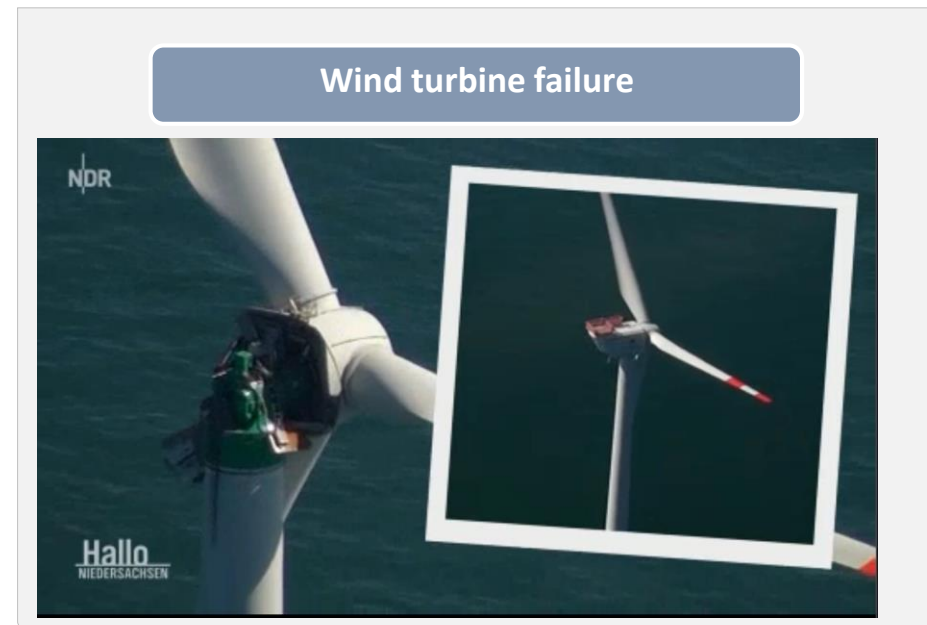
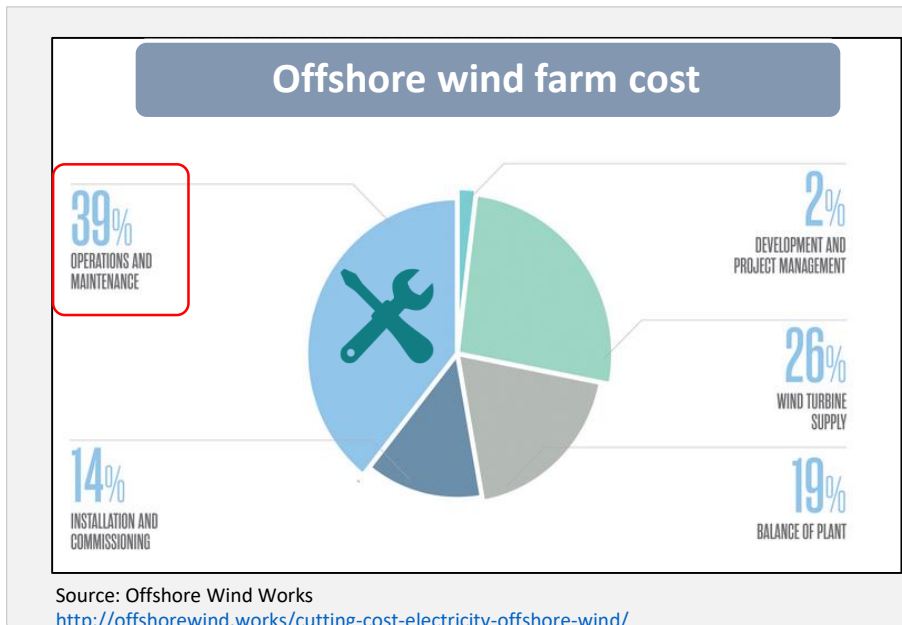
**O&M cost**

**Triple<sup>(1)</sup>**

**offshore (\$170/MWh<sup>(1)</sup>)**



(1) International Renewable Energy Agency, 2014

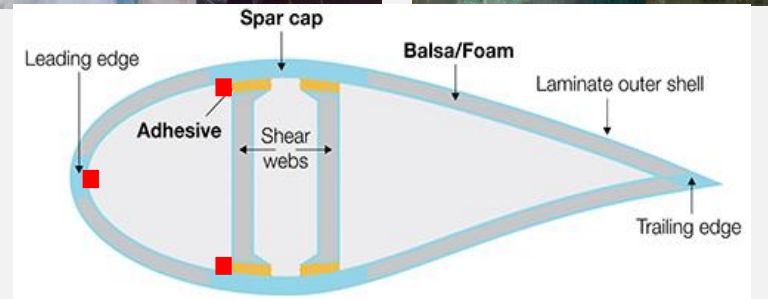
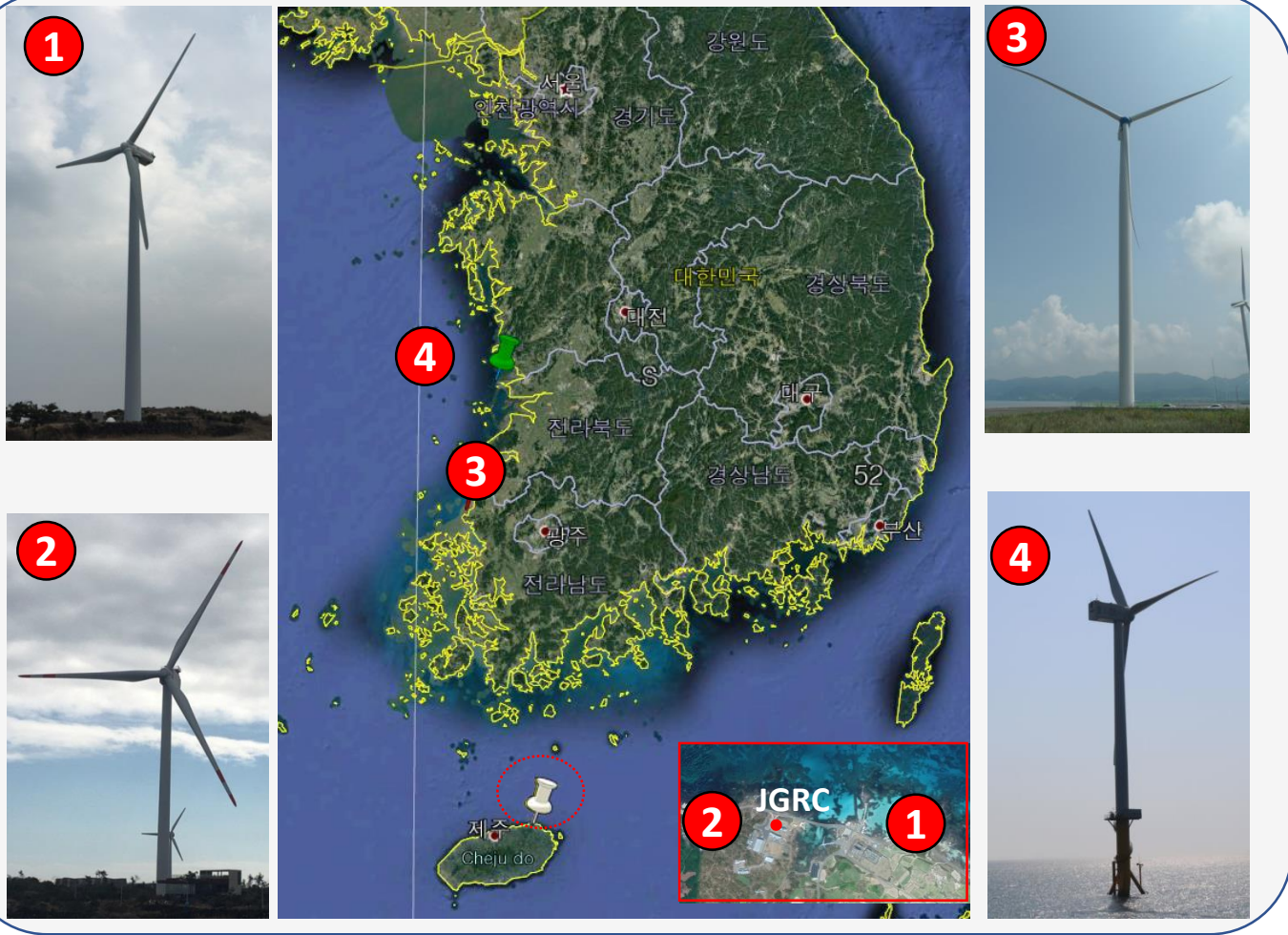


## 2. 프로젝트 개요

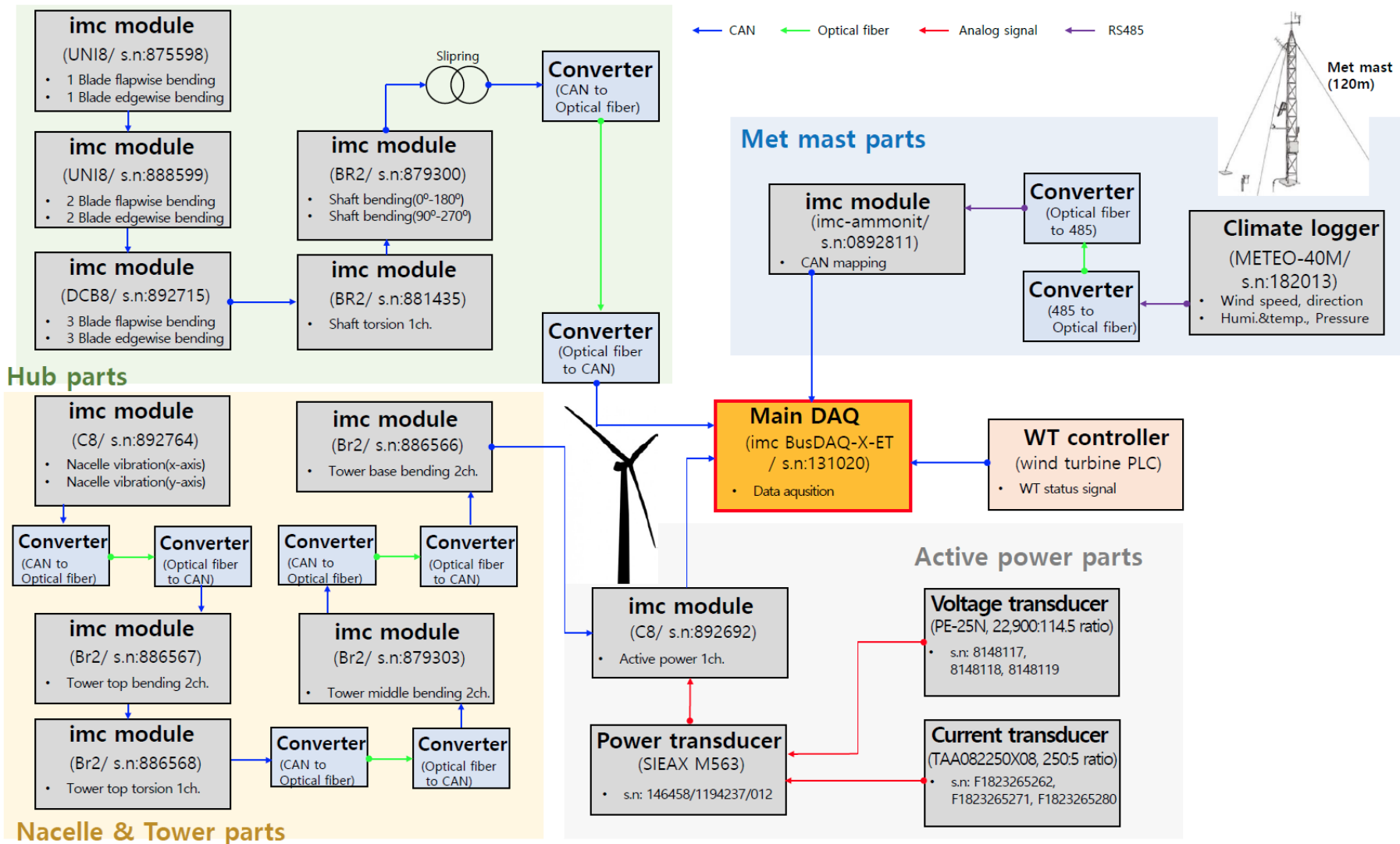




## 2. 프로젝트 개요



# 2. 프로젝트 개요

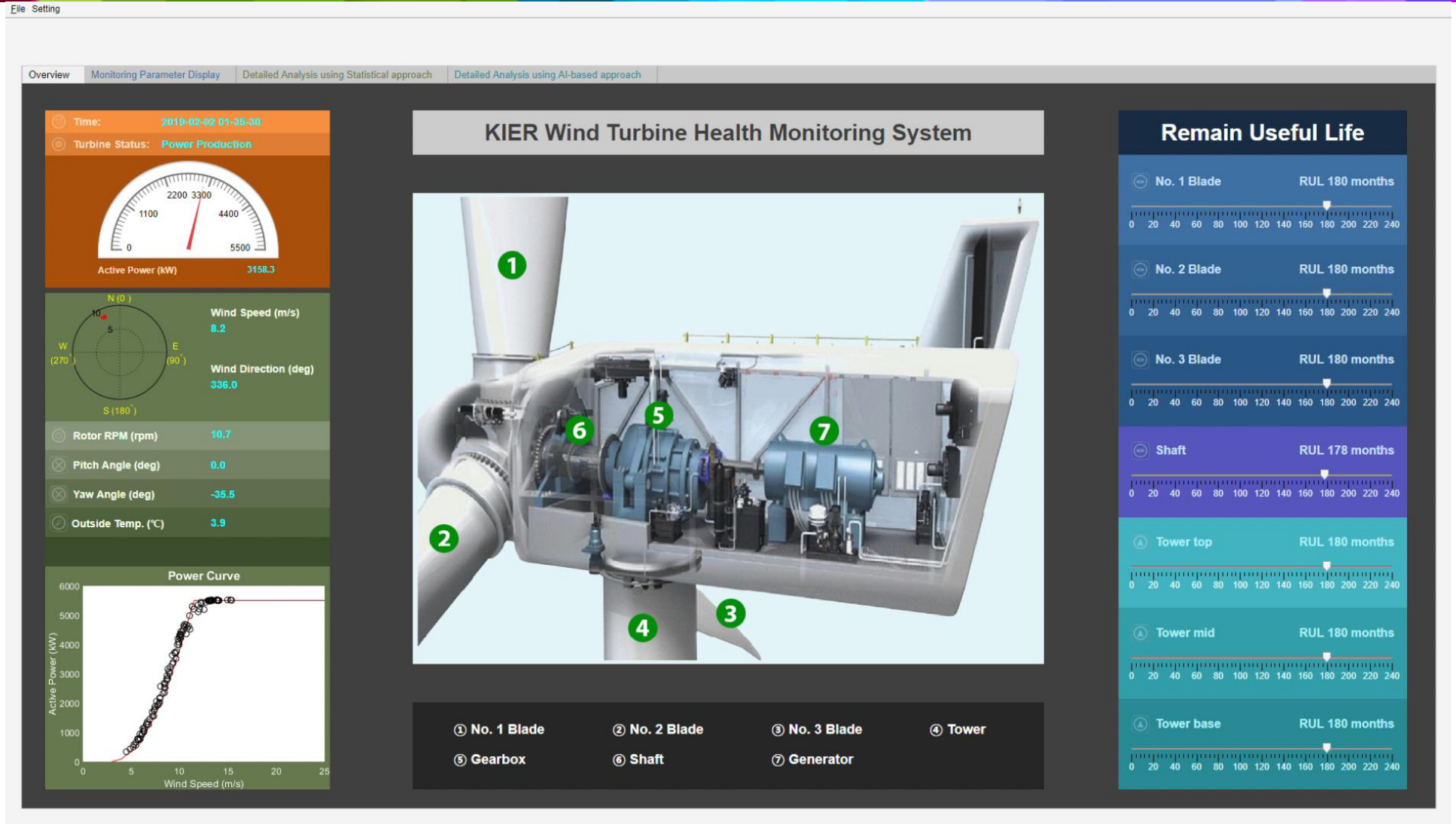




## 2. 프로젝트 개요

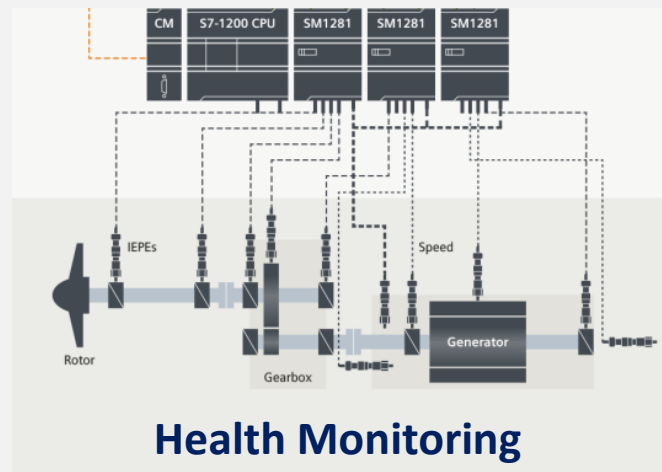
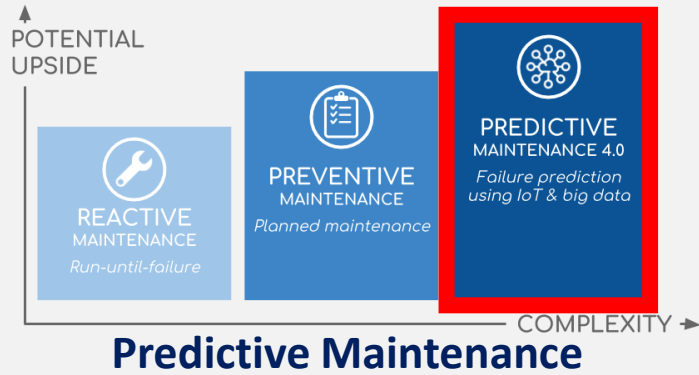
WTheMos

MATLAB  
App Designer



### 3. 기술적인 해결과제

#### 해상 풍력 유지보수



8,000 components  
3,000 signals



8,000 components

# of sensors ↑

Data storage ↑

Complex monitoring system

3,000 signals

Big data

Data evaluation not easy



## 4. 해결방안 및 결과

8,000 components  
3,000 signals



8,000 components

# of sensors ↑

Data storage ↑

Complex monitoring system

3,000 signals

Big data

Data evaluation not easy

## 4. 해결방안 및 결과



**8,000 components**

- # of sensors ↑
- Data storage ↑
- Complex monitoring system



**8,000 components**

- Sensorless load estimation
- Data storage ↓
- Simple monitoring system

**3,000 signals**

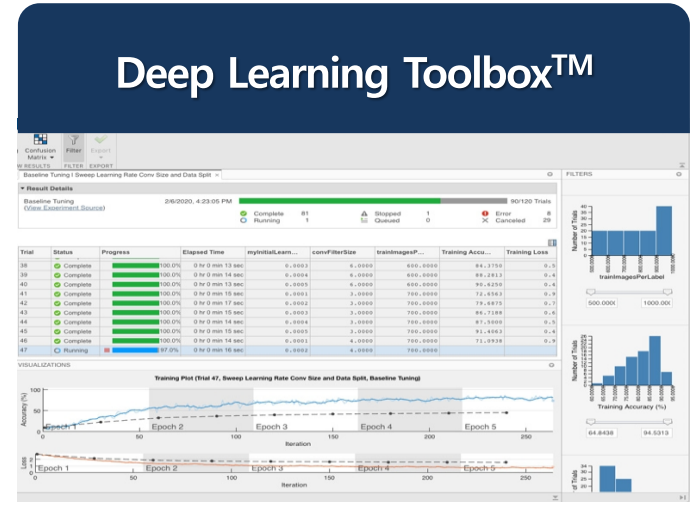
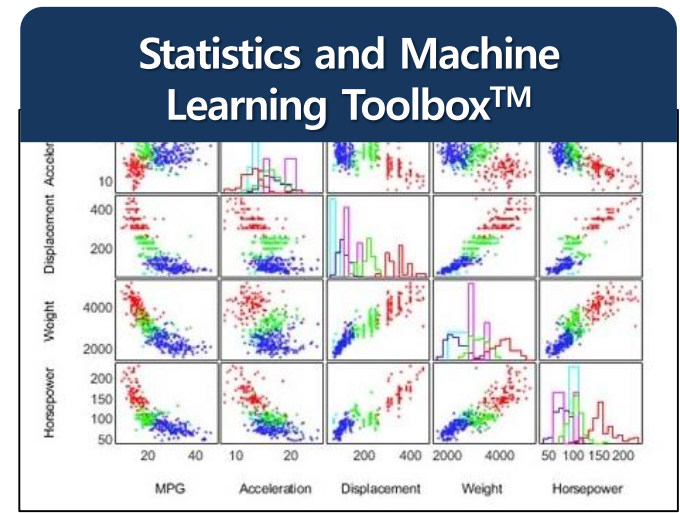
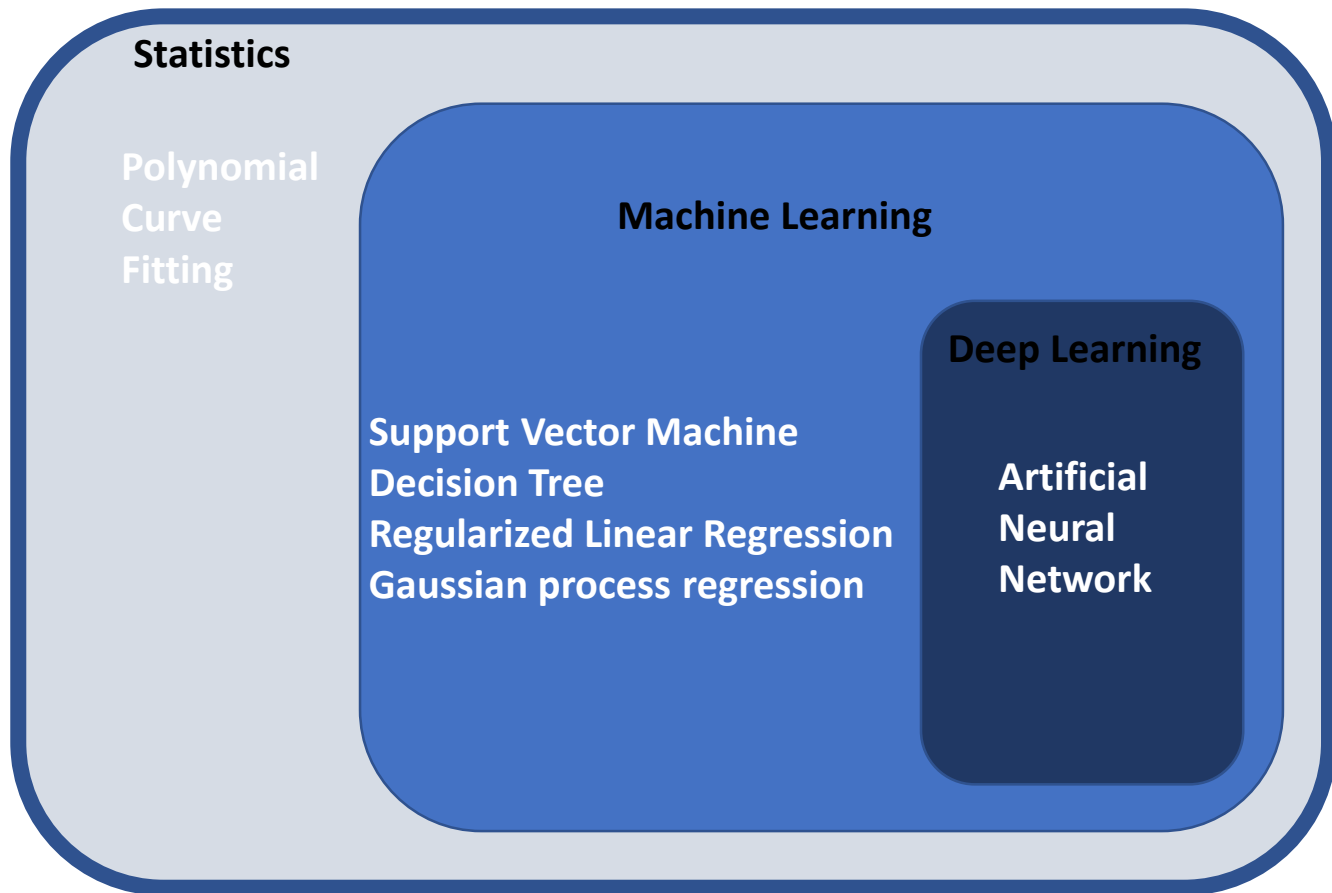
- Big data
- Data evaluation not easy



**3,000 signals**

- Machine learning/  
Deep learning
- Supervised learning

# 4. 해결방안 및 결과



# 4. 해결방안 및 결과



IEC 61400-13

Edition 1.0 2015-12

INTERNATIONAL  
STANDARD

NORME  
INTERNATIONALE



Wind turbines –  
Part 13: Measurement of mechanical loads

Capture matrix

	min. V	4	5	6	7	8	9	10	11	12	13	14	15
	max. V	5	6	7	8	9	10	11	12	13	14	15	16
min. I	max. I												
0	0.05									1	1	0	0
0.05	0.07	0	1	2	15	17	14	20	4	10	21	8	5
0.07	0.09	2	7	23	25	31	36	38	20	24	36	12	5
0.09	0.11	2	20	23	22	15	26	17	10	17	11	3	2
0.11	0.13	8	12	13	8	7	12	6	1	0	1	1	0
0.13	0.15	9	4	6	2	2	2	0	0	1	0	0	0
0.15	0.17	4	4	1	0	0	0	0	0	0	0	0	0
0.17	0.19	3	0	0	0	0	0	0	0	0	0	0	0
0.19	0.21	1	0	1	0	0	0	0	0	0	0	0	0
0.21	0.23	0	0	0	0	0	0	0	0	0	0	0	0
0.23	0.25	0	0	0	0	0	0	0	0	0	0	0	0
0.25	0.27	0	0	0	0	0	0	0	0	0	0	0	0
0.27	0.29	0	0	0	0	0	0	0	0	0	0	0	0
0.29		0	0	0	0	0	0	0	0	0	0	0	0
<b>Total No. of data</b>		<b>29</b>	<b>48</b>	<b>69</b>	<b>72</b>	<b>72</b>	<b>90</b>	<b>81</b>	<b>35</b>	<b>53</b>	<b>70</b>	<b>24</b>	<b>12</b>



## 4. 해결방안 및 결과



물리량	내용	단위
Acc_FB	나셀 앞/뒤 방향 가속도	m/s <sup>2</sup>
Acc_RL	나셀 좌/우 방향 가속도	m/s <sup>2</sup>
Base_135	타워 하부 남북 방향 모멘트	Nm
Base_225	타워 하부 동서 방향 모멘트	Nm
Blade1_edge	1번 블레이드 날방향 모멘트	Nm
Blade1_flap	1번 블레이드 평활 방향 모멘트	Nm
Blade2_edge	2번 블레이드 날방향 모멘트	Nm
Blade2_flap	2번 블레이드 평활 방향 모멘트	Nm
Blade3_edge	3번 블레이드 날방향 모멘트	Nm
Blade3_flap	3번 블레이드 평활 방향 모멘트	Nm
HSS_RPM	고속 축에서 측정한 로터 회전속도	rpm
Shaft_0_180	메인샤프트 수직 방향 모멘트	Nm
Shaft_90_270	메인샤프트 수평 방향 모멘트	Nm
Shaft_torque	메인샤프트 토크	Nm
Top_135_315	타워 상부 남북 방향 모멘트	Nm
Top_45_225	타워 상부 동서 방향 모멘트	Nm
Top_torsion	타워 상부 비틀림 모멘트	Nm

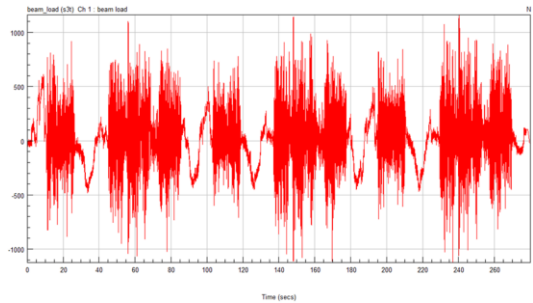


물리량	내용	단위
Con_Wind_Speed	나셀의 측정 풍속	m/s
WT_Active_Power	유효전력	W
WT_Current_R	R상 전류	A
WT_Current_S	S상 전류	A
WT_Current_T	T상 전류	A
WT_Frequency	출력 주파수	Hz
WT_Volt_R	R상 전압	V
WT_Volt_S	S상 전압	V
WT_Volt_T	T상 전압	V
WS	풍속	m/s
WD	풍향	deg
Temp	기온	deg.C
Barometer	공기 밀도	kg/m <sup>3</sup>

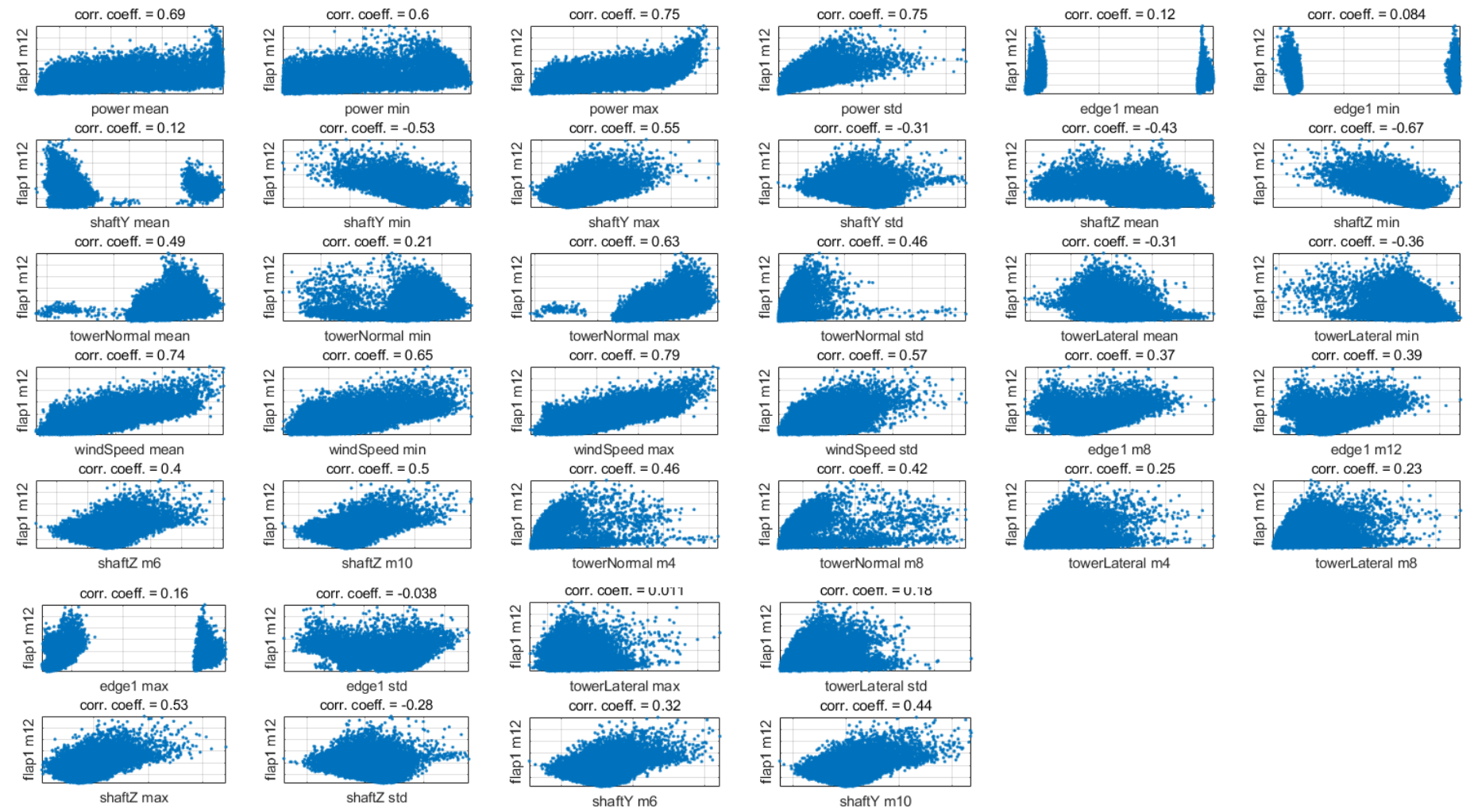
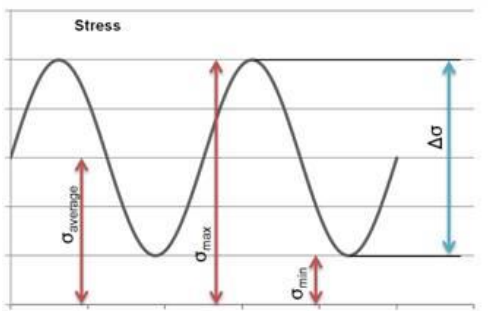
# 4. 해결방안 및 결과

	1	2	3	4	5	6	7	8	9	10	11	12				
	windSpeed_mean	windSpeed_min	windSpeed_max	windSpeed_std	power_mean	power_min	power_max	power_std	edgeMiddle2_mean	edgeMiddle2_min	edgeMiddle2_max	edgeMiddle2_std				
1	13.3519	12.3583	14.4323	0.4723	5.5056e+03	5.4272e+03	5.5876e+03	35.7961	14.0337	-1.2685e+03	1.2724e+03	824.6686				
2	13.7755	12.6809	14.8471	0.4734	5.5095e+03											
3	13.9176	12.8192	14.5245	0.4246	5.5156e+03											
4	13.1492	11.6208	13.9253	0.4847	5.5087e+03											
5	12.0303	11.0678	13.6488	0.5017	5.5000e+03	13	14	15	16	17	18	19	20	21	22	23
6	12.8839	11.9896	13.9714	0.5096	5.5179e+03	edge2_mean	edge2_min	edge2_max	edge2_std	flap2_mean	flap2_min	flap2_max	flap2_std	shaftY_mean	shaftY_min	shaftY_max
7	12.8719	11.6208	13.9714	0.5935	5.5160e+03	231.9582	-5.5602e+03	6.0545e+03	3.9908e+03	9.0837e+03	7.7600e+03	1.0542e+04	477.6832	136.1214	-4.9970e+03	5.1280e+03
8	13.4223	12.4505	14.7089	0.5403	5.5255e+03	373.2918	-5.5014e+03	6.0240e+03	3.9720e+03	9.0988e+03	7.2252e+03	1.0868e+04	671.0471	162.3956	-5.7062e+03	5.7755e+03
9	13.6958	11.6669	15.0776	0.8776	5.5179e+03	158.6989	-5.7299e+03	6.3509e+03	4.0063e+03	9.1644e+03	7.5131e+03	1.1112e+04	691.2266	243.2598	-5.6512e+03	5.5989e+03
10	13.7661	12.4965	15.0776	0.5409	5.5149e+03	503.4331	-5.5099e+03	6.1331e+03	3.9930e+03	9.3665e+03	7.7838e+03	1.0485e+04	533.2822	44.0891	-4.7235e+03	5.0501e+03
11	10.2736	9.1781	11.8052	0.6895	4.5074e+03	424.7382	-5.6880e+03	6.5262e+03	4.0410e+03	9.9945e+03	7.7136e+03	1.1874e+04	768.9536	225.5006	-6.2702e+03	5.9132e+03
12	9.9263	9.1320	11.1599	0.5077	4.2651e+03	685.4726	-5.2333e+03	6.5132e+03	4.0269e+03	1.0333e+04	8.8106e+03	1.1819e+04	619.6000	37.3227	-6.1629e+03	5.6407e+03
13	10.6052	9.9155	11.3904	0.3562	4.7107e+03	579.1110	-5.5800e+03	6.8384e+03	4.0390e+03	1.0026e+04	8.5262e+03	1.1828e+04	612.2715	177.9292	-6.2664e+03	5.0710e+03
14	10.1878	9.3163	11.0678	0.4562	4.7088e+03	360.7589	-5.6089e+03	6.6879e+03	4.0049e+03	9.6902e+03	7.0943e+03	1.2118e+04	968.3278	169.1623	-6.4297e+03	5.8619e+03
15	9.9777	9.2702	10.8834	0.3449	4.1977e+03	632.7549	-5.8481e+03	6.5861e+03	4.0289e+03	9.8266e+03	7.5607e+03	1.1714e+04	850.9692	30.7747	-6.6386e+03	6.2939e+03
16	10.6378	9.7311	11.7130	0.4951	4.5404e+03	155.8912	-5.7469e+03	6.2762e+03	3.9577e+03	9.1465e+03	7.4138e+03	1.0382e+04	532.5268	315.0101	-5.3132e+03	5.7783e+03
17	10.4728	9.5929	11.2521	0.4659	4.8705e+03	1.1847e+03	-4.9658e+03	7.2088e+03	4.0913e+03	1.1125e+04	9.6268e+03	1.2054e+04	559.1693	-29.9494	-5.6815e+03	4.5792e+03
18	10.9918	10.1460	11.8974	0.4929	4.7985e+03	1.1291e+03	-4.9522e+03	6.9656e+03	4.1008e+03	1.0892e+04	9.8641e+03	1.2597e+04	517.0241	-69.8489	-5.3502e+03	5.1916e+03
19	10.5129	8.9476	11.5747	0.7127	5.0217e+03	1.1824e+03	-4.9217e+03	7.1387e+03	4.0863e+03	1.1388e+04	9.9950e+03	1.2605e+04	562.9461	-110.9959	-5.1157e+03	4.7681e+03
20	9.6664	7.7954	10.7912	0.6853	4.8345e+03	1.0406e+03	-5.1417e+03	7.1285e+03	4.0729e+03	1.1225e+04	9.4816e+03	1.3137e+04	704.5618	48.4478	-5.8439e+03	6.0584e+03
21	10.2263	9.1320	11.2060	0.5440	4.0363e+03	1.0354e+03	-5.0167e+03	7.1591e+03	4.0812e+03	1.0796e+04	9.8356e+03	1.1893e+04	462.7255	29.4157	-5.3264e+03	4.9390e+03
22	10.4727	9.3624	11.2060	0.4212	4.4449e+03	1.1928e+03	-4.7486e+03	7.0126e+03	4.0244e+03	1.1195e+04	9.8463e+03	1.2554e+04	686.8629	-17.1752	-5.5467e+03	6.1648e+03
23	9.6371	8.4867	10.5147	0.4128	4.4470e+03	1.2677e+03	-4.8267e+03	7.1755e+03	4.0020e+03	1.1522e+04	9.9420e+03	1.3343e+04	738.3616	-143.3361	-5.8857e+03	5.7508e+03
24	10.5718	9.5468	11.2060	0.3854	3.5749e+03	1.0364e+03	-4.7871e+03	7.0556e+03	4.1030e+03	1.1453e+04	9.6196e+03	1.2676e+04	572.2755	54.7603	-5.7167e+03	5.5657e+03
25	10.4278	9.3624	11.4826	0.4429	4.3426e+03	1.2961e+03	-4.8114e+03	7.2286e+03	4.1063e+03	1.1653e+04	1.0630e+04	1.2885e+04	408.0646	-43.4218	-5.0369e+03	5.0188e+03
26	9.9750	8.6250	10.8373	0.4987	4.7883e+03	1.2270e+03	-5.1598e+03	7.4396e+03	4.1056e+03	1.1392e+04	9.7374e+03	1.2907e+04	519.8431	-85.1749	-5.4651e+03	5.5970e+03
27	10.0572	8.6250	10.8834	0.4702	3.7645e+03	1.0051e+03	-5.1078e+03	7.1178e+03	4.0961e+03	1.0576e+04	8.7719e+03	1.1983e+04	693.9640	-1.7852	-6.0044e+03	5.6682e+03
28	10.2904	9.0859	11.7591	0.6695	3.6499e+03	1.0087e+03	-4.8832e+03	7.0318e+03	4.0726e+03	1.1107e+04	8.7100e+03	1.2729e+04	829.5137	61.5619	-5.5543e+03	6.0176e+03
29						1.0440e+03	-5.0133e+03	7.0510e+03	4.0435e+03	1.1027e+04	9.4590e+03	1.2527e+04	677.8695	62.3329	-5.8126e+03	5.5429e+03
30						942.3690	-4.8691e+03	6.6303e+03	4.0435e+03	1.0112e+04	8.8207e+03	1.1834e+04	591.5691	0.2669	-5.0065e+03	5.1099e+03
31						1.0489e+03	-4.8583e+03	7.0595e+03	4.0659e+03	1.1005e+04	9.4096e+03	1.2416e+04	553.1429	72.5309	-5.2049e+03	5.0653e+03
32						1.2818e+03	-4.7978e+03	7.0239e+03	4.1214e+03	1.1390e+04	1.0217e+04	1.2668e+04	469.0063	-24.5126	-4.7178e+03	4.9874e+03
33						916.9424	-4.9398e+03	6.9492e+03	4.0444e+03	1.0274e+04	8.4602e+03	1.1451e+04	575.7548	101.6990	-6.4525e+03	5.6274e+03
34						867.5855	-4.9811e+03	6.9498e+03	3.9984e+03	1.0188e+04	8.4049e+03	1.1770e+04	749.2089	102.7235	-5.7490e+03	5.5381e+03

# 4. 해결방안 및 결과

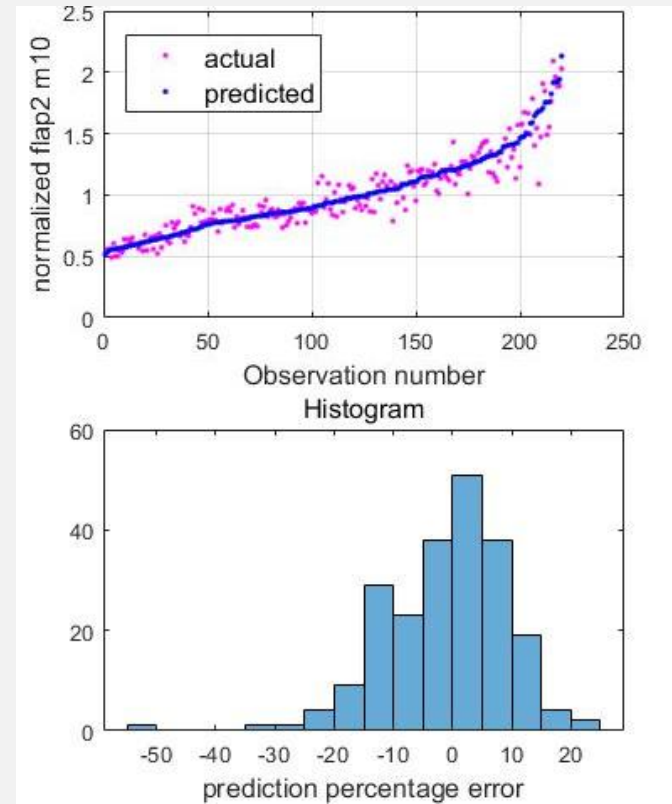
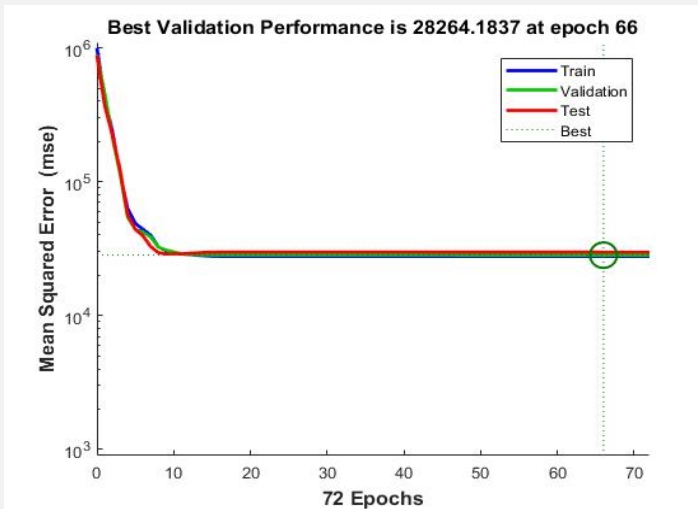
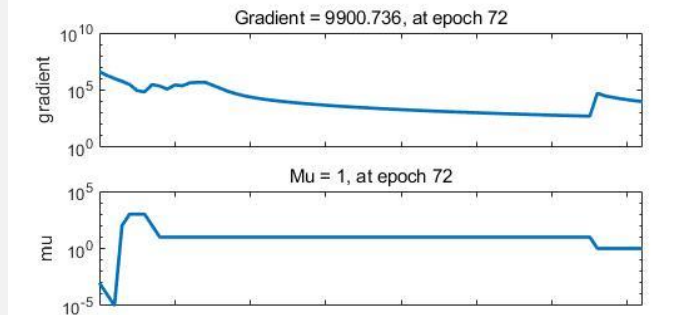


**Damage Equivalent Load**



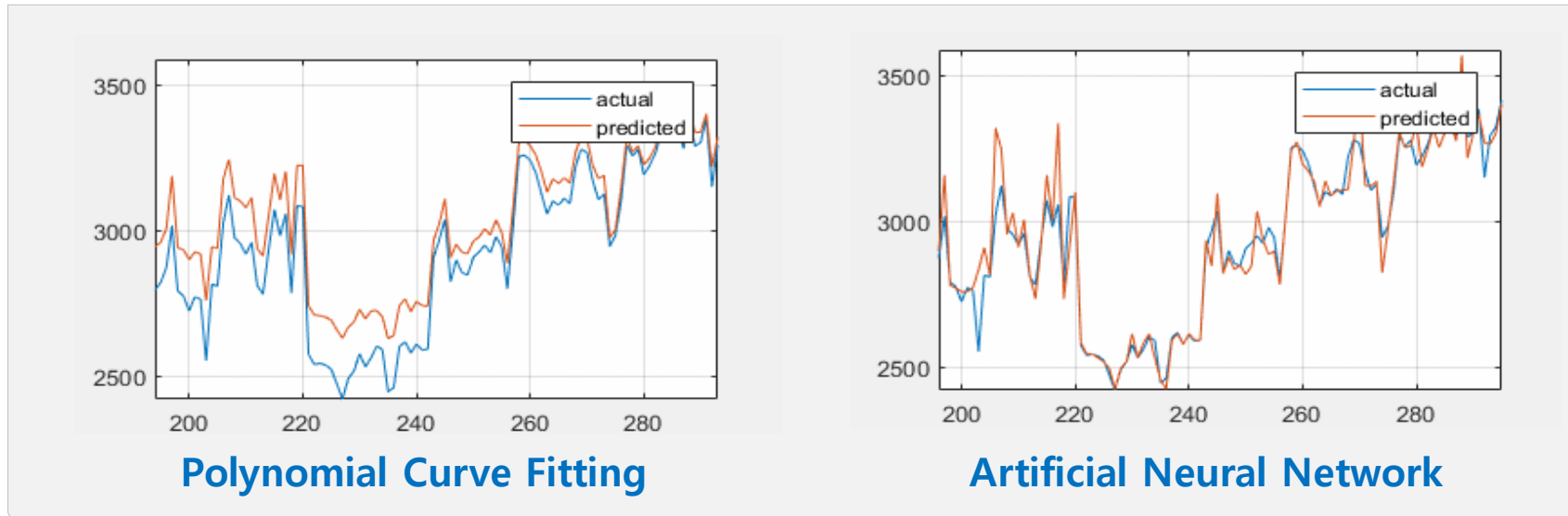
# 4. 해결방안 및 결과

## Deep Learning Toolbox™

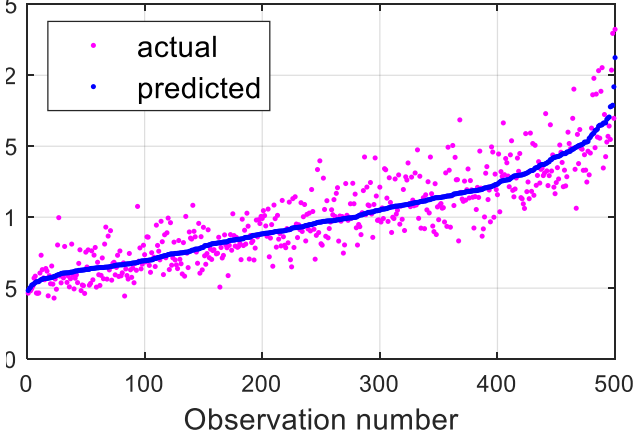




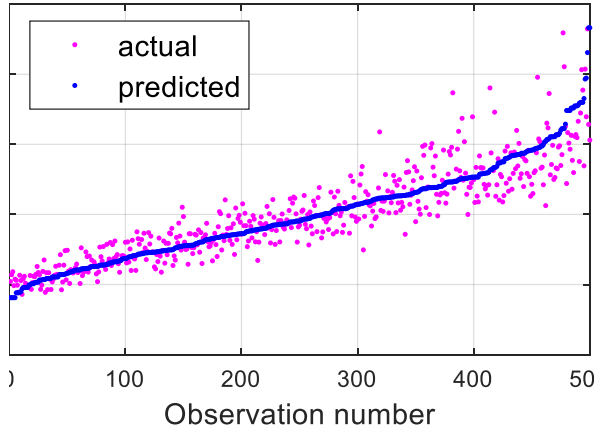
# 4. 해결방안 및 결과



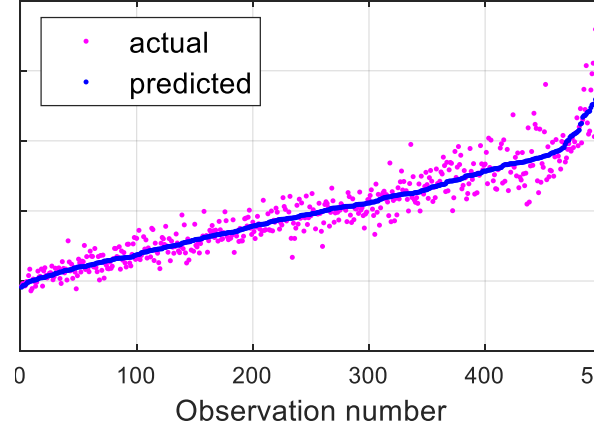
Polynomial Curve Fitting, R=0.8894, MAPE=12.07 %



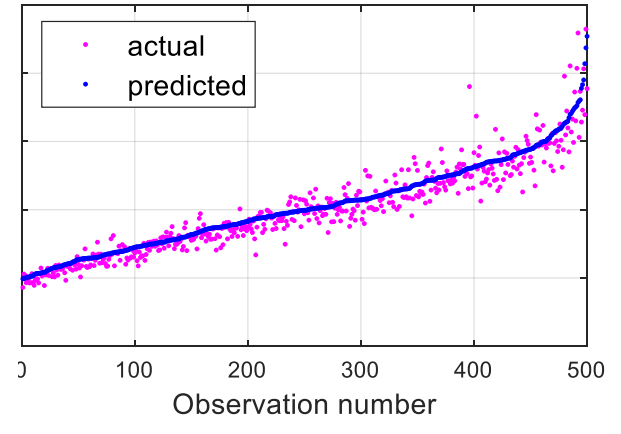
Tree, R=0.897, MAPE=10.44 %



Linear, R=0.9498, MAPE=7.576 %



NN, R=0.956, MAPE=7.126 %



## 4. 해결방안 및 결과



Flapwise bending moment of the blade 1 (m=12)

1Hz DEL	WT-1	WT-2	WT-3	WT-4
1 <sup>st</sup>	<b>ANN</b>	<b>ANN</b>	<b>ANN</b>	<b>ANN</b>
2 <sup>nd</sup>	<b>Linear</b>	<b>Linear</b>	<b>Tree</b>	<b>Linear</b>
3 <sup>rd</sup>	<b>Tree</b>	<b>Tree</b>	<b>Linear</b>	<b>Tree</b>
4 <sup>th</sup>	<b>Polynomial</b>	<b>Polynomial</b>	<b>Polynomial</b>	<b>Polynomial</b>

ANN : Artificial Neural Network  
 Linear : Regularized Linear Regression  
 Tree : Decision Tree  
 Polynomial : Polynomial Curve Fitting

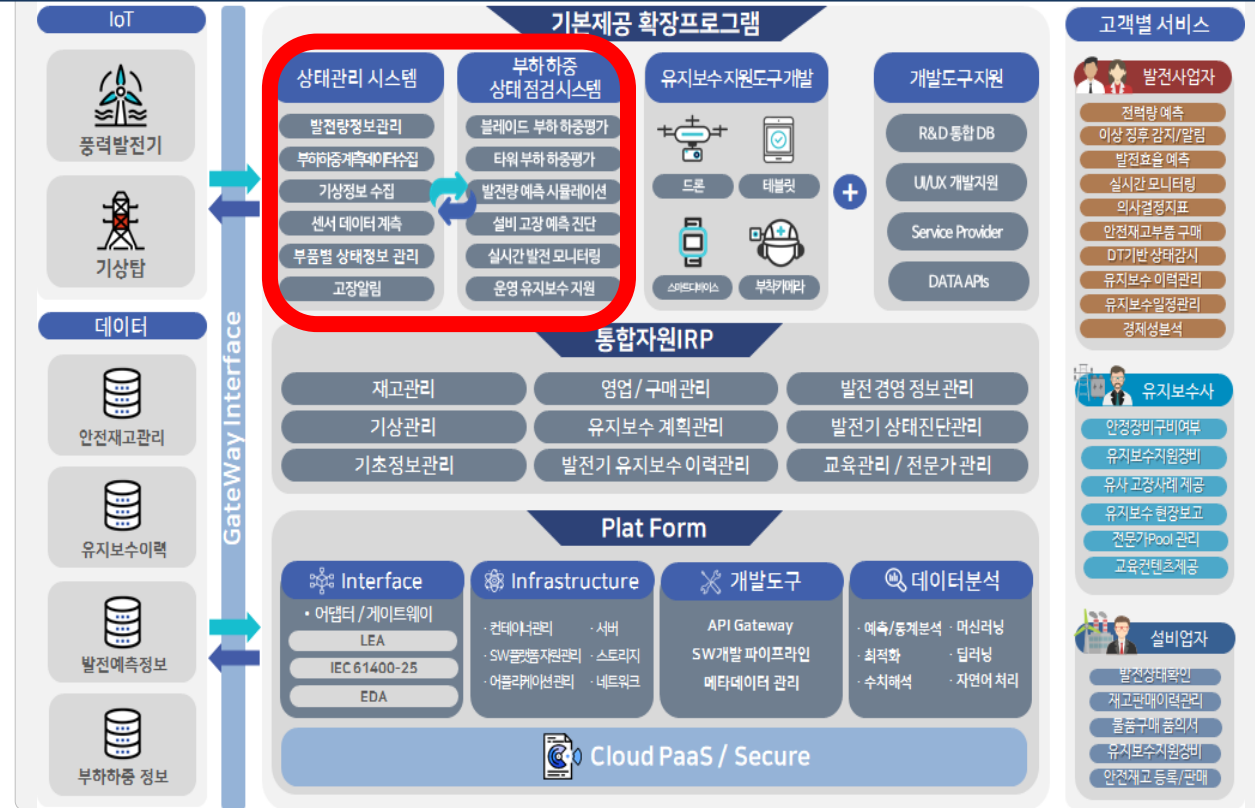
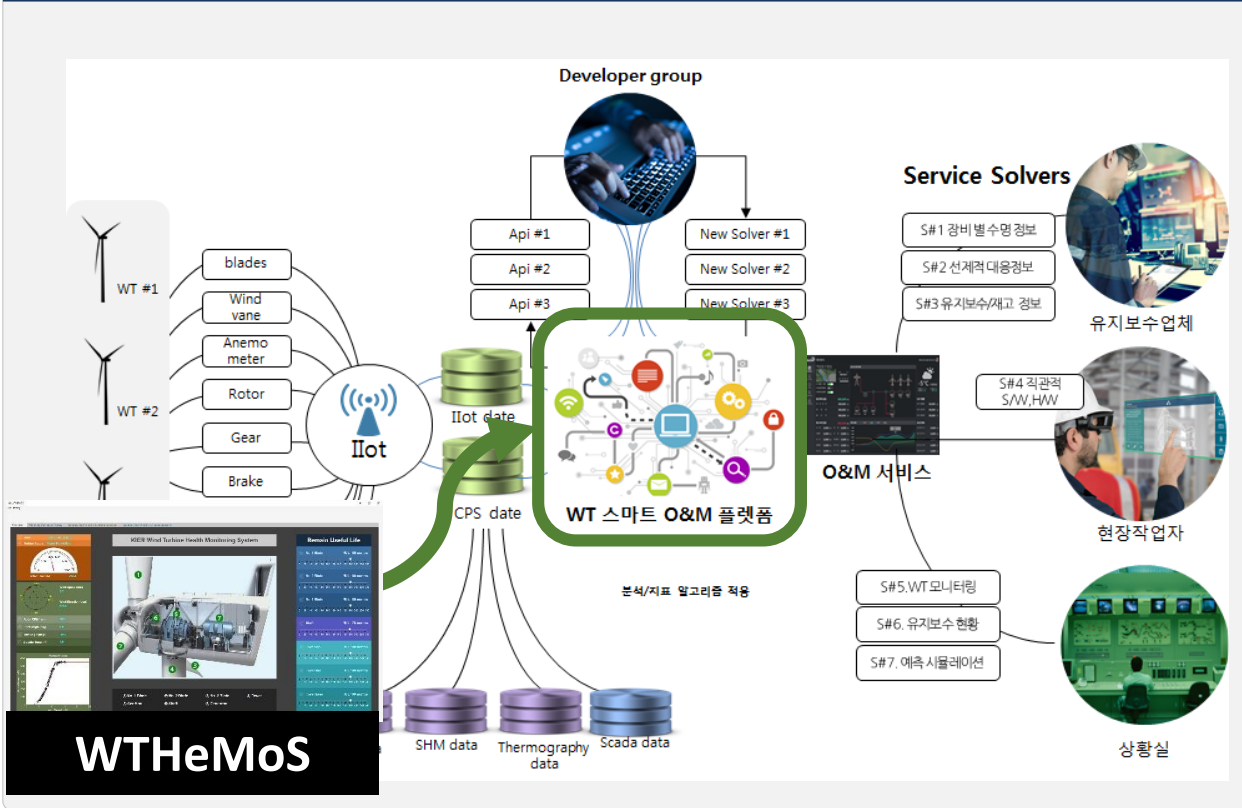
## 4. 해결방안 및 결과



1Hz DEL	Prediction Score			
	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>
Flapwise bending moment of the blade 1 (m=12)	<b>ANN</b>	Linear	Tree	Polynomial
Edgewise bending moment of the blade 1 (m=12)	<b>ANN</b>	Tree	Linear	Polynomial
Shaft tilt moment (m=6)	<b>ANN</b>	Linear	Tree	Polynomial
Shaft yaw moment (m=6)	Polynomial	Linear	<b>ANN</b>	Tree
Tower bottom normal moment (m=4)	Linear	<b>ANN</b>	Tree	Polynomial
Tower bottom lateral moment (m=4)	Linear	<b>ANN</b>	Polynomial	Tree

# 5. 결과 및 정리

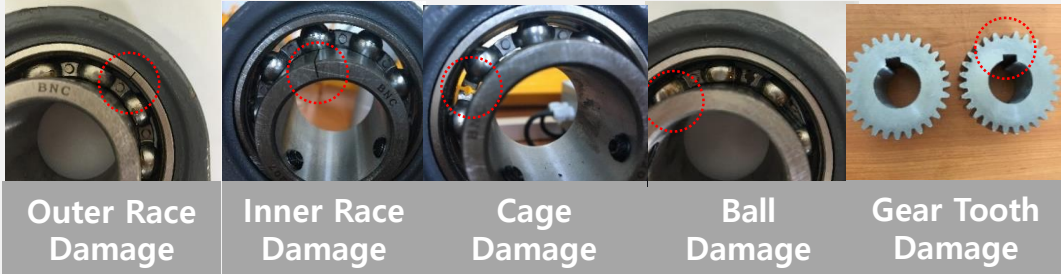
## Wind Power Plant Smart O&M Platform





# 6. 다음 과제

## Bearing Fault Categories



**KIER Bearing Fault Simulator Analysis Program**

Set Configuration | Time Data Analysis | FFT Analysis | Spectrogram | Envelope Analysis

**KIER Bearing Fault Simulator**

Measurement Channel Description	Operation & Bearing Details
Ch.1 : Servo Motor 감속기 Z-dir.	Sampling Frequency (Hz) 10000
Ch.2 : 감속기 Drive-End Z-dir.	Revolution per Minute (RPM) 1800
Ch.3 : 감속기 Non Drive-End Z-dir.	Number of Balls or Rollers 9
Ch.4 : Gear Box Z-dir.	Ball or Roller Diameter (d, mm) 11.22
Ch.5 : Gear Box Y-dir.	Pitch Diameter (D, mm) 54
Ch.6 : Bearing Housing Z-dir.	Contact Angle (alpha, degrees) 0
Ch.7 : Bearing Housing Y-dir.	
Ch.8 : Baseplate Z-dir.	
Ch.9 : Baseplate Y-dir.	
Ch.10 : Baseplate X-dir.	

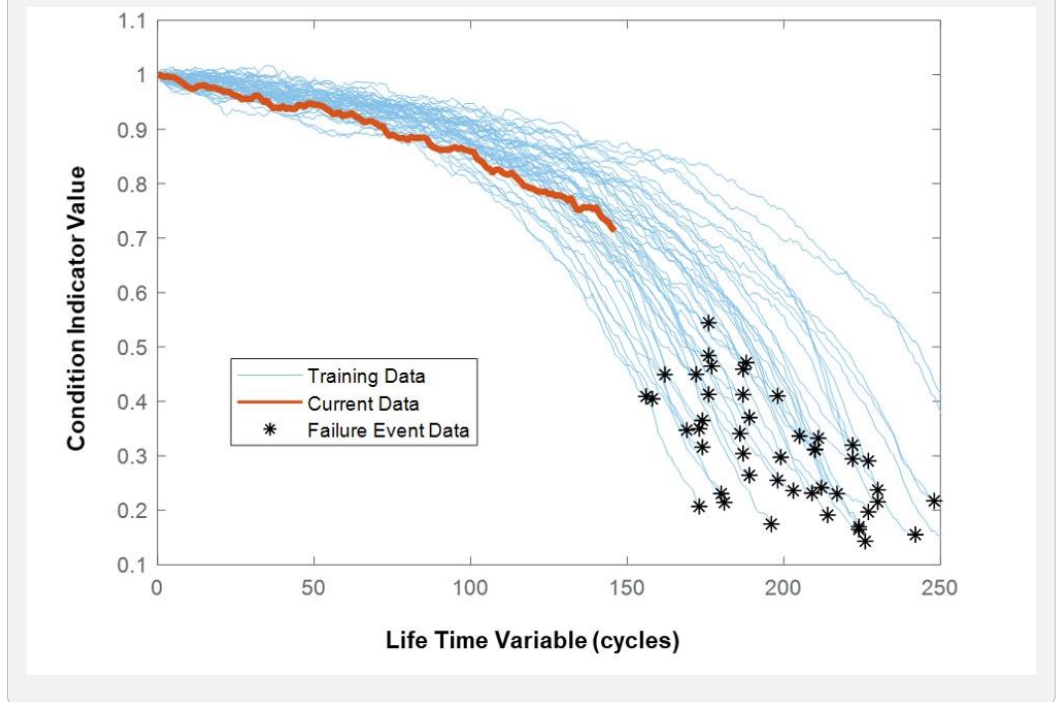
**Calculated Bearing Frequencies (Hz)**

Fundamental Train Frequency	11.88
Ball Pass Frequency of Inner Race	163.05
Ball Pass Frequency of Outer Race	106.95
Ball Spin Frequency	69.08
Bearing Fault Frequency	138.16

Data Load



## Predictive Maintenance Toolbox™

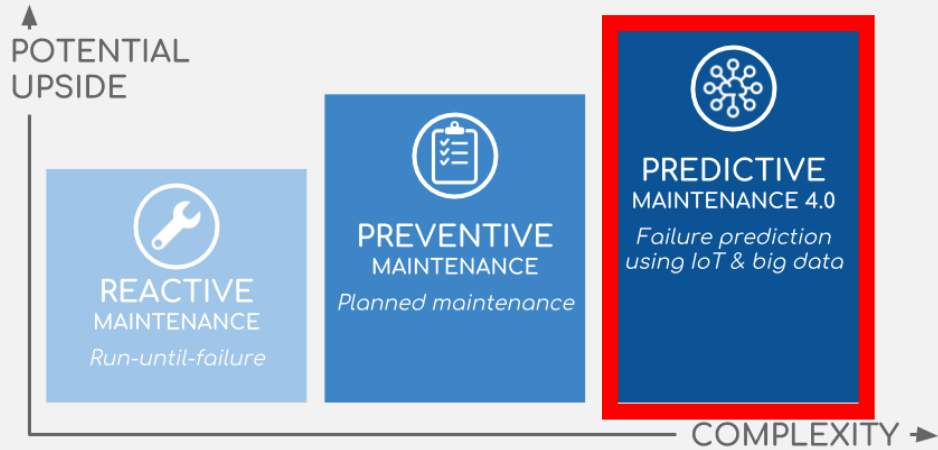




# 7. 결론

## 해상 풍력 유지보수

### Predictive Maintenance



8,000 components  
3,000 signals

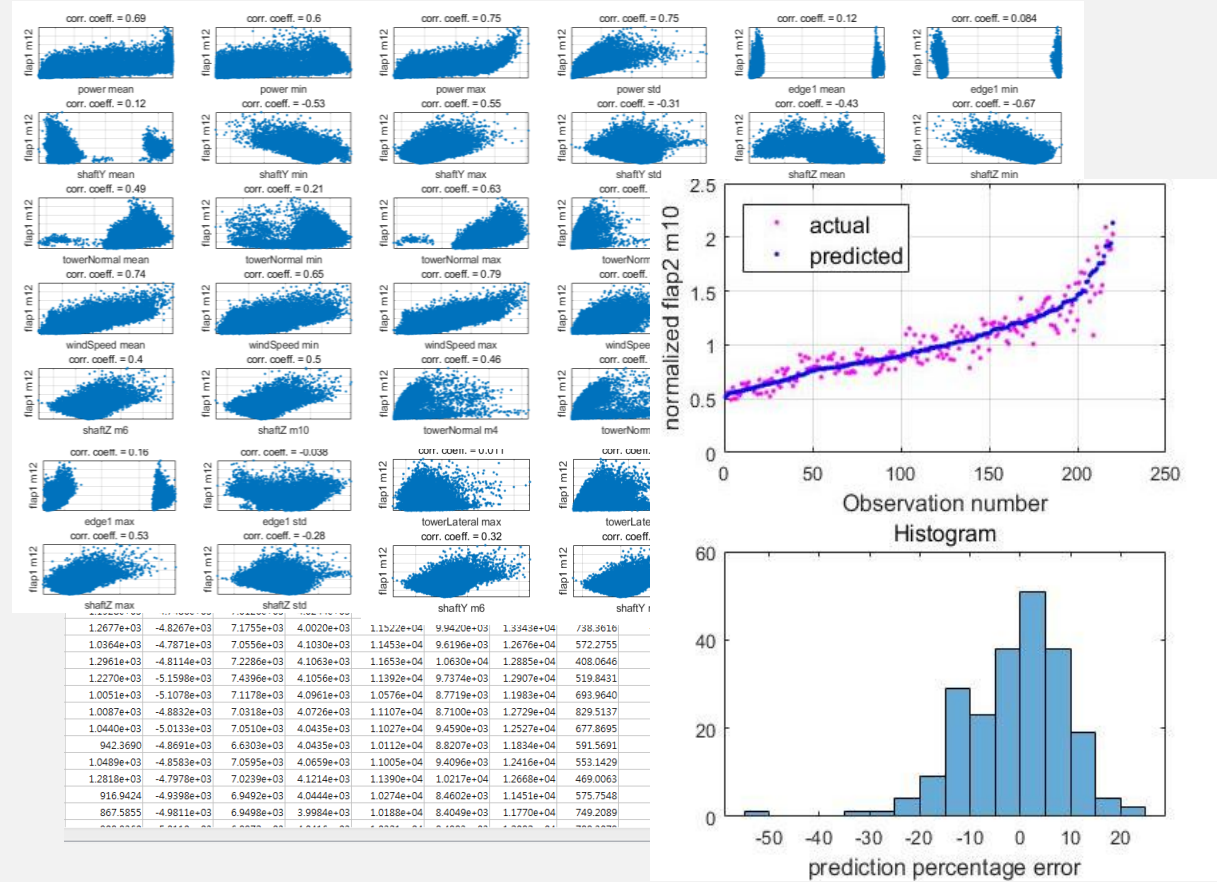
### Machine Learning

Data Usage ↓  
# of Sensors ↓

LCOE ↓

## Statistics and Machine Learning Toolbox™

## Deep Learning Toolbox™



# MATLAB EXPO

## 감사합니다

풍력발전기 예지적 유지보수를 위한 MATLAB 프로그램의 활용  
최정철, 한국에너지기술연구원

