

750kW급 직접 구동형 풍력 발전기의 제어 시스템 개발

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Control System Development of 750kW Direct Drive Wind Turbine Generator

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Key words : Nacelle controller (나셀 제어기), Pitch controller (피치 제어기), Torque controller (토크 제어기), Operating control system (운전 제어 시스템), Automatic yawing (요잉 제어), Wind turbine generator (풍력발전기), Wind energy converter (풍력발전기)

Abstract : 풍력발전기에 있어서 보호 및 제어 시스템은 그 효율, 성능, 안전 및 수명까지도 영향을 미칠 수 있는 중요한 구성요소이다. 따라서 제어 시스템은 풍력발전기의 최대 효율 및 가동률을 확보하여야 하며 풍력발전기에 문제가 발생할 경우 즉시 가동을 정지할 수 있도록 안전성을 확보할 수 있도록 설계되어야 한다. 본 연구에서는 “750kW급 Gearless형 풍력발전시스템 개발” 과제의 일환으로 수행되었던 풍력발전기용 제어시스템의 설계 및 제작 과정과 상용제품으로서의 본 제어 시스템을 소개하고자 한다.

1. 서론

제어시스템은 풍력발전기의 제어 및 보호를 수행하는 중요 요소로서 그 효율, 성능, 안전 및 수명까지도 영향을 미칠수 있는 중요 구성 요소이다. 어떠한 상태에서도 풍력발전기의 안정성을 유지하고 최대한의 출력을 생산하여 풍력발전기의 성능을 향상시키는 것이 제어시스템의 기본목표라 할 수 있다.

IEC 61400-1에 따르면 제어 및 보호 요구 사항은 다음과 같다.

1) 제어 시스템의 요구 사항

- Power limitation
- Rotor speed
- Connection of the electrical load
- Start-up and shutdown procedures
- Shutdown at loss of electrical network or electrical load
- Cable twist limits
- Alignment to the wind.

2) 보호 시스템의 요구 사항

- Overspeed

- Generator overspeed or fault
- Excessive vibration
- Failure to shut down following network loss, disconnection from the network or loss of load
- Abnormal cable twist (due to nacelle rotation by yawing)

2. 제어 시스템의 개념 설계

제어시스템의 기능을 크게 분류하면 제어기능과 보호기능으로 분류할 수 있다. 제어기능은 풍력발전기의 동작을 원활하게 수행하도록 하여 설계단계에서 고려된 성능특성을 갖기 위한 기능이며, 보호기능은 풍력발전기가 외부 또는 내부의 외란으로부터 안전하게 동작하도록 하기 위한 기능이다.

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2.1 Wind Turbine의 작동 Mechanism

Wind Turbine의 전반적인 작동은 Fig. 1에 따라서 이루어지며, 매 순간의 상태는 정지 상태와 운전 상태로 나눌 수 있다. 각 작동상태를 세분화하면 Table 1과 같다. Wind Turbine에서 발생할 수 있는 모든 결함을 파악하여 이에 따른 적절한 정지 절차를 수립하는 것은 제어시스템에서 반드시 수행되어야 할 과제이다.

Table 1. Procedure and Status of Wind Turbine

Item	Description
Ready for Operation	저풍속 또는 에러 등에 의한 발전기 정지 후 에러 원인 제거에 의한 발전기 재 운전 대기 상태
Normal Operation	풍력발전시스템이 정상적으로 운전되는 상태
Normal Stop	N-STOP 1 경미한 에러발생에 의한 발전기 정지 상태
	N-STOP 2 발전기의 일부 부품에 영향을 미칠 수 있는 문제에 의한 발전기 정지 상태
Emergency Stop	N-STOP 1 발전기에 악영향을 미칠 수 있는 문제에 의한 발전기 정지 상태
	N-STOP 2 Personnel Safety를 위한 정지 상태
Service/Maintenance	유지·보수를 위한 발전기 정지 상태

2.2 Error Level에 따른 Error Code List

Table 2는 발생가능한 모든 Error에 대하여 그 위험도에 따라서 총 6종류의 에러 레벨을 설정하였고, 각 레벨에 따라서 그에 적합한 동작 특성을 가지도록 하였다.

Table 2. Error Level에 따른 Error Code List

Error Code	Error Name	Error Description	Action / Severity
101	Def. winding temp warning	Def. Winding temp > limit 1	Warning
102	Def. winding temp alarm	Def. Winding temp > limit 2	Alarm
103	Def. winding temp critical	Def. Winding temp > limit 3	Critical
104	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
105	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
106	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
107	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
108	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
109	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
110	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
111	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
112	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
113	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
114	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
115	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
116	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
117	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
118	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
119	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
120	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
121	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
122	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
123	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
124	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
125	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
126	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
127	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
128	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
129	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
130	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
131	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
132	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
133	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
134	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
135	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
136	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
137	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
138	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
139	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
140	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
141	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
142	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
143	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
144	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
145	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
146	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
147	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
148	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
149	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
150	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
151	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
152	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
153	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
154	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
155	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
156	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
157	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
158	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
159	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
160	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
161	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
162	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
163	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
164	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
165	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
166	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
167	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
168	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
169	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
170	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
171	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
172	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
173	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
174	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
175	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
176	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
177	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
178	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
179	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
180	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
181	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
182	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
183	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
184	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
185	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
186	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
187	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
188	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
189	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
190	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
191	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
192	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
193	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
194	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
195	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
196	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
197	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning
198	Def. bearing temp alarm	Def. Bearing temp > limit 2	Alarm
199	Def. bearing temp critical	Def. Bearing temp > limit 3	Critical
200	Def. bearing temp warning	Def. Bearing temp > limit 1	Warning

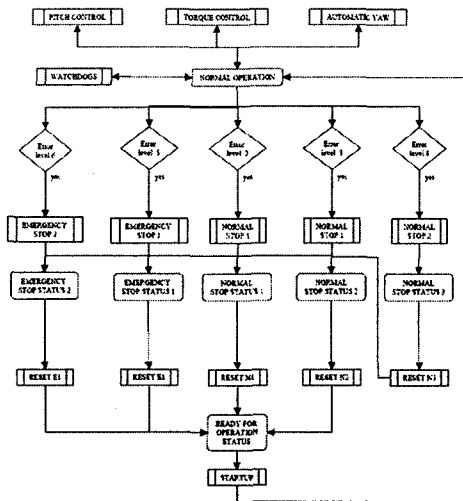


Fig. 1 Flowchart of Basic Scheme

2.3 Parameter 및 Set Point List

Set Point는 제어가 풍력발전기의 운전 상황을 판단하는 기준이며 이 값을들 기준으로 각 상황에 맞는 적절한 조치를 취하게 된다. 본 제어 시스템에 반영된 Parameter 및 Set Point의 일부를 아래 Table 3에 나타내었다.

Table 3. Parameter 및 Set Point List

Code	Name	Description	Unit	Value
200001	Def. wind speed	Def. wind speed	km/h	10.0
200002	Def. wind speed	Def. wind speed	km/h	15.0
200003	Def. wind speed	Def. wind speed	km/h	20.0
200004	Def. wind speed	Def. wind speed	km/h	25.0
200005	Def. wind speed	Def. wind speed	km/h	30.0
200006	Def. wind speed	Def. wind speed	km/h	35.0
200007	Def. wind speed	Def. wind speed	km/h	40.0
200008	Def. wind speed	Def. wind speed	km/h	45.0
200009	Def. wind speed	Def. wind speed	km/h	50.0
200010	Def. wind speed	Def. wind speed	km/h	55.0
200011	Def. wind speed	Def. wind speed	km/h	60.0
200012	Def. wind speed	Def. wind speed	km/h	65.0
200013	Def. wind speed	Def. wind speed	km/h	70.0
200014	Def. wind speed	Def. wind speed	km/h	75.0
200015	Def. wind speed	Def. wind speed	km/h	80.0
200016	Def. wind speed	Def. wind speed	km/h	85.0
200017	Def. wind speed	Def. wind speed	km/h	90.0
200018	Def. wind speed	Def. wind speed	km/h	95.0
200019	Def. wind speed	Def. wind speed	km/h	100.0
200020	Def. wind speed	Def. wind speed	km/h	105.0
200021	Def. wind speed	Def. wind speed	km/h	110.0
200022	Def. wind speed	Def. wind speed	km/h	115.0
200023	Def. wind speed	Def. wind speed	km/h	120.0
200024	Def. wind speed	Def. wind speed	km/h	125.0
200025	Def. wind speed	Def. wind speed	km/h	130.0
200026	Def. wind speed	Def. wind speed	km/h	135.0
200027	Def. wind speed	Def. wind speed	km/h	140.0
200028	Def. wind speed	Def. wind speed	km/h	145.0
200029	Def. wind speed	Def. wind speed	km/h	150.0
200030	Def. wind speed	Def. wind speed	km/h	155.0
200031	Def. wind speed	Def. wind speed	km/h	160.0
200032	Def. wind speed	Def. wind speed	km/h	165.0
200033	Def. wind speed	Def. wind speed	km/h	170.0
200034	Def. wind speed	Def. wind speed	km/h	175.0
200035	Def. wind speed	Def. wind speed	km/h	180.0
200036	Def. wind speed	Def. wind speed	km/h	185.0
200037	Def. wind speed	Def. wind speed	km/h	190.0
200038	Def. wind speed	Def. wind speed	km/h	195.0
200039	Def. wind speed	Def. wind speed	km/h	200.0
200040	Def. wind speed	Def. wind speed	km/h	205.0
200041	Def. wind speed	Def. wind speed	km/h	210.0
200042	Def. wind speed	Def. wind speed	km/h	215.0
200043	Def. wind speed	Def. wind speed	km/h	220.0
200044	Def. wind speed	Def. wind speed	km/h	225.0
200045	Def. wind speed	Def. wind speed	km/h	230.0
200046	Def. wind speed	Def. wind speed	km/h	235.0
200047	Def. wind speed	Def. wind speed	km/h	240.0
200048	Def. wind speed	Def. wind speed	km/h	245.0
200049	Def. wind speed	Def. wind speed	km/h	250.0
200050	Def. wind speed	Def. wind speed	km/h	255.0
200051	Def. wind speed	Def. wind speed	km/h	260.0
200052	Def. wind speed	Def. wind speed	km/h	265.0
200053	Def. wind speed	Def. wind speed	km/h	270.0
200054	Def. wind speed	Def. wind speed	km/h	275.0
200055	Def. wind speed	Def. wind speed	km/h	280.0
200056	Def. wind speed	Def. wind speed	km/h	285.0
200057	Def. wind speed	Def. wind speed	km/h	290.0
200058	Def. wind speed	Def. wind speed	km/h	295.0
200059	Def. wind speed	Def. wind speed	km/h	300.0
200060	Def. wind speed	Def. wind speed	km/h	305.0

2.4 Control Algorithm

Normal Operation 운전시 피치각과 발전기 토크는 피치 및 토크 제어기에 의하여 제어된다. 정격 부하보다 낮은 부하 상태에서 미리 정의된 토크-속도 곡선에 의하여 토크는 제어된다. 토크-속도 곡선은 로터의 최적 TSR (Tip Speed Ratio) 에서 운전되도록 선정된다. 정격 로터 각속도이상의 영역에서는 일정 출력이 생산되게끔 토크가 제어된다.

Drive Train 진동을 억제하며 시스템에의 감쇠를 증가시키기 위하여 Drive Train Damper Filter를 아래와 같이 적용하고, Drive Train 진동모드의 가진을 방지하기 위하여 발전기 회전 속도의 측정값을 Notch Filter를 사용하여 해당 성분을 제거한다.

또한 측정된 풍속 신호의 급격한 변동 성분을 제거하기 위하여 Low Pass Filter를 적용한다.

제어 영역은 Fig. 2.에서와 같이 I, II, III 3부분으로 나뉘어진다. 정격 부하이하에서 제어 영역 I, II는 활성화되고, 정격 부하시 제어 영역 III가 활성화된다.

제어 영역 III에서 피치 컨트롤러가 활성화되면서 토크 컨트롤러와 더불어 작용하여 로터 각속도는 정격 각속도 상하 ±10%영역이내에 유지된다. 이때, 풍속에 따라서 피치각 변화와 출력 변화간의 비선형성으로인해 수정 인자가 적용된다.

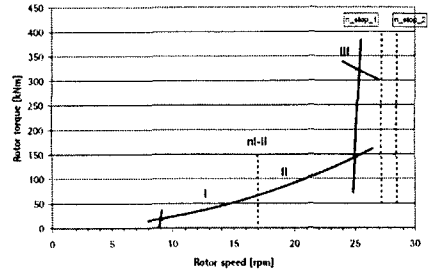


Fig. 2. Control Zone for Pitch and Torque Control

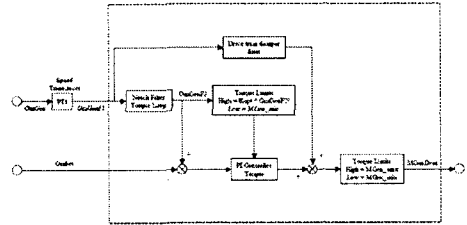


Fig. 3. Block Diagram of Torque Control

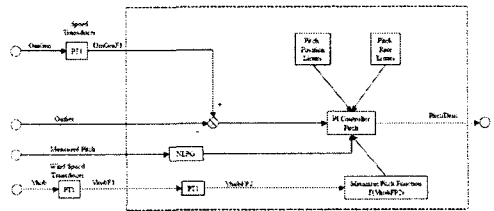


Fig. 4. Block Diagram of Pitch Control

1) PI Controller for Pitch Controller

$$\phi = \phi^* + y$$

$$y = K_{p-pitch} / G(x - x^*) + (T/2)K_{i-pitch} / G(x + x^*), \quad x = \omega - \omega_s$$

2) PI Controller for Torque Controller

$$y = y^* + K_{p-torque}(x - x^*) + (T/2)K_{i-torque}(x + x^*), \quad x = \omega - \omega_s$$

3) Drive Train Damper Filter

$$G(s) = \frac{2\xi\omega s(1+s\tau)}{s^2 + 2\xi\omega s + \omega^2}$$

4) Nitch Filter

$$G(s) = \frac{s^2 + 2\xi_1\omega_1s + \omega_1^2}{s^2 + 2\xi_2\omega_2s + \omega_2^2}$$

5) PT1 Filter

$$G(s) = \frac{\omega}{s + \omega}$$

2.5 제어 시스템 Hardware 구성개념도

본 풍력발전기에 적용된 전체 제어 시스템은 Fig. 5.과 같이 총 3개의 제어기로 구성된다.

- Nacelle Controller : 풍력발전기의 제어 및 보호 시스템의 주제어기로서 모든 감시 및 제어기능을 총괄적으로 수행하는 장치
- Pitch Controller : 피치 제어와 관련된 모든 정보들은 나셀 제어기로 취합되며, 그에 따른 해당요구 동작정보를 받아 블레이드의 각각을 제어하는 장치
- Bottom Controller : 타워의 바닥에 위치하여 나셀 제어기와 외부간의 입-출력 역할을 수행

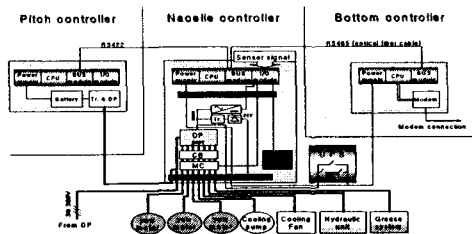


Fig. 5 풍력발전기 제어시스템 전체 개념도

3. 상세설계

3.1 PLC I/O List

Table 4. PLC I/O List

CPU		DIGITAL INPUT		DIGITAL OUTPUT		ANALOG INPUT		ANALOG OUTPUT	
1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

3.2 제어 시스템 Hardware 구성도

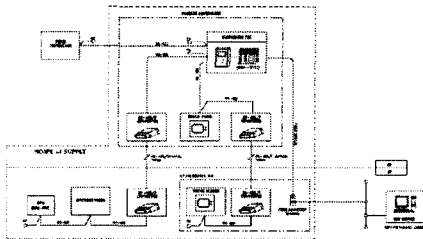


Fig. 6. Control System의 구성도

3.3 Pitching System 구성도

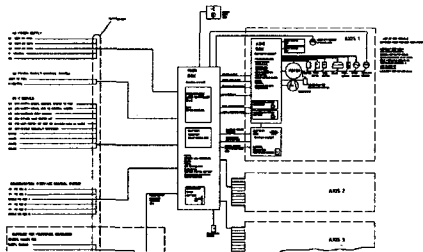


Fig. 7. Pitching System 구성도

4. 제어 프로그램의 구성 및 구현

Initial ; 각종 I/O 및 특수모듈의 이상 유무를 판단, Ai_out ; 아날로그 입력 신호를 처리, Rotor ; 엔코더 신호를 받아 RPM 계산, Temperature ; PT100으로 온도 계산, Pitch controller와 Pitch reference ; 제어영역에 따른 각을 계산하며 계산된 값을 Pitch Controller에 전달, Yaw_drive ; 풍향계 신호를 처리 한 후 설계된 제어 알고리즘에 따라 Yaw System을 제어한다. Grid ; 인버터, 컨버터, 디지털 파워 미터에서 현재 발생하는 전력량 및 토크 제어에 관한 데이터를 통신을 통하여 처리. 중앙제어기에서 가장 중요한 부분인 Basic scheme은 모든 장치에서 분석된 결과를 취합하여 전체 시스템에 관한 상황판단과 프로그램에서 발생하는 에러에 대하여

적절한 모드를 선정하고 그에 맞는 조치를 취한다.

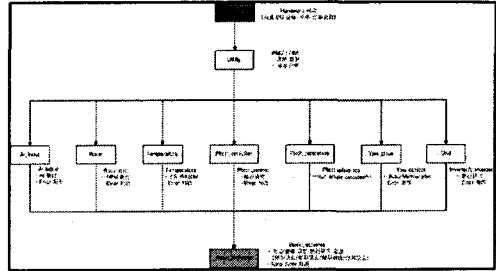


Fig. 8. Ladder Diagram 전체 구성도

5. 제어기 제작

5.1 Nacelle controller

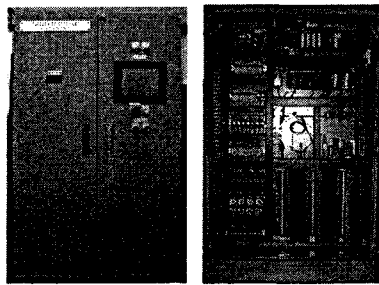


Fig. 9. Nacelle controller 내·외부

5.2 Bottom controller

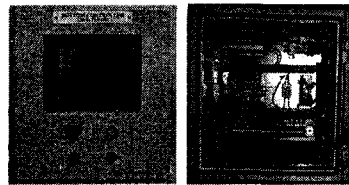


Fig. 10. Bottom controller 내·외부

5.3 Pitching system

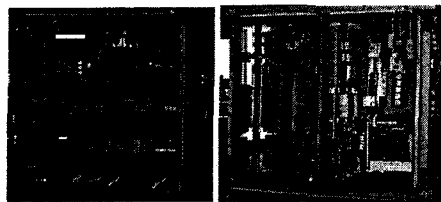


Fig. 11. Pitch system 장치별 사진

6. 결론

본 논문에서는 풍력발전기의 운전 및 보호에 필수적인 제어 시스템의 개발에 있어서 그 요구 사양, 개념 설계, 상세 설계, 실제 제작에 대하여 설명하였다. 개발된 제어시스템은 현재 Shop test중이며, 향후 Field test를 거쳐 국산 750kW급 풍력발전기에 적용되어 시장에 공급될 예정이다.