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APPICATION RESULTS OF REAL-TIME AMPACITY ESTIMATION SYSTEM AND INTELLIGENT POWER CABLE SYSTEM

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ABSTRACT

In this paper, first two projects applying real-time ampacity estimation system (R-TAS^{TM}) on 345kV cable system in Korea will be introduced focusing on specification and operation results. And as an essential part of the future "intelliGrid", intelligent power cable system functions and operation results will be explained.

KEYWORDS

R-TAS^{TM}, rating current, DTS, CTM, DRS, intelligent power cable system

INTRODUCTION

Recently, the studies on thermal transient behaviour inside and outside power cable and its rating current applying DTS (Distributed Temperature Sensor) technology have been carried out around the world for the purpose of monitoring cable temperature and increasing current carrying capacity [1~3].

Furthermore just like new word "intelliGrid" from EPRI, future EHV cable system will be required not only conventional mission such as reliable energy transmission but also new functions such as self diagnostics, communication and sensing means etc [4].

This worldwide trend can be thought to derive from utilities' new needs which are real-time monitoring present condition and finally increasing operation efficiency of their assets safely.

In Korea, to prepare this future cable system, national R&D project centred on LS Cable have started in 2001, and the team have developed R-TAS^{TM} after testing it in live transmission cable system in 2003 [1], and finally in 2005 this new system could be successfully applied in first two KEPCO projects [5]. One was Shinyangjae-Gwachon 345kV underground cable system and the other was Bukbusan-Nambusan 345kV cable system.

On the meanwhile the extension of this monitoring system has accelerated the development and application of optical fibre composite power cable and accessory. In Korea, applying this cable system, new transmission cable system named intelligent power cable system was successfully installed in Gumi in 2005 [6].

The reason why we named intelligent power cable system is that it does not just transport electric power but it has optical fibre temperature sensor and optical communication media transporting monitoring information such as partial discharge signal, moving image, and submergence information and remote control signal for water pump and ventilation fan and so on.

In this paper, first two projects applying R-TAS^{TM} on 345kV oil filled cable system in Korea will be introduced focusing on specification and operation results. And as an essential part of the future "intelligrid", intelligent power cable system functions and operation results will also be explained.

SPECIFICATION OF R-TAS^{TM} IN KOREA

The specification of R-TAS^{TM} in Korea was firstly made by KEPCO and revised in 2006 [7]. Main characteristics of this specification are that optical sensor fibre forms a loop configuration which one part of it is installed on cable jacket to measure cable jacket temperature and the other part of loop is installed on tunnel ceiling to measure ambient temperature and monitor fire. Table 1 shows specification of R-TAS^{TM} in Korea.

Table 1 Main specification of R-TAS^{TM} in Korea

Item	Specification
DTS*	•Measurement processing: Double-ended •Number of channel: 6 (12 connectors) •Applicable fibre: Multimode GI 50/125um •Temperature accuracy: within ±1.5℃ •Temperature resolution: within 1.5℃ •Spatial resolution: typical 2m •Sampling resolution: typical 1m •Outdoor cabinet: IP 62 grade (Automatic temperature/humidity control) •DTS PC: Industrial type (> CPU 3.6GHz) •UPS: More than 2 hours back-up •Main alarm - Fire: within 10 sec (> 70℃) - Abrupt overheating: within 30 sec (> 10℃ between two measurements) - Joint overheating: within 30 sec (> 5℃ between two phases of joints) •Real time self diagnostics - Optical power of laser - Optical loss of sensor fibre •Automatic change to single-ended measurement when fibre breaks

CTM**	•CPU: > 3.6GHz •Calculation of cable conductor, insulator, metallic sheath for entire cable route. •Submission of experimental results about thermal parameters in algorithm. •Main alarm - Cable overheating: within 2 min (>70℃) - Abrupt overheating: within 2 min (>10℃ between two calculations)
DRS***	•CPU :>3.6GHz •Estimation of dynamic rating & emergency rating current (2,4,8,12,24,48 hours) •Submission of experimental results about thermal parameters in algorithm. •Main alarm - Cable overloading: within 10 min

DTS* : Distributed Temperature Sensor
CTM** : Conductor Temperature Monitoring Module
DRS*** : Dynamic Rating System

In order to meet the above specification, DTS was installed in every 4 km and temperature and distance were calibrated in every power cable joint and sensor fibre joint. CTM was designed to calculate conductor, insulator and metallic sheath of maximum 50km long within 2 min using DTS and load current data. DRS estimated continuous rating current, dynamic rating current and emergency rating current at cable conductor hotspot.

OPERATION RESULTS

Shinyangjae-Gwachon project

Shinyangjae-Gwachon transmission line consists of 4 circuits of 8.9 c-km long 345kV oil-filled cable and laying condition is tunnel. It delivers electric power to central office and commercial area in Seoul. Figure 1 shows outline of Shinyangjae –Gwachon transmission line.

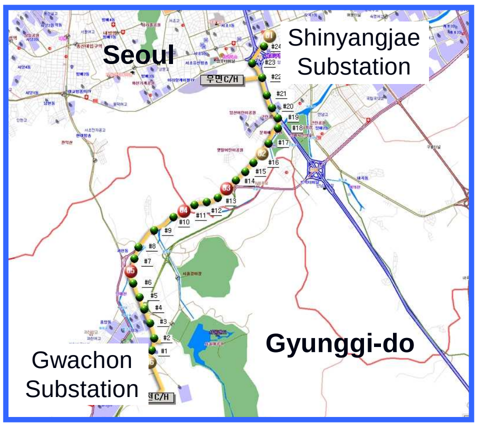

Fig. 1 Shinyangjae-Gwachon transmission line

The applied R-TAS™ system is composed of one master station apart from about 20km from the site and total 3 DTS systems in local tunnel site.

Total 4 multimode optical fibre sensors of 2 cores for each circuit were attached on centre cable of trefoil configuration and also attached on all 3 phases of cable joint with extra length of 5m. One multimode optical fibre sensor of 8 cores was installed on the ceiling of the tunnel and 4 optical sensors of 2 cores and one optical sensor of 8 cores were spliced together. 4 channels of DTS were used applying double-ended processing. The reason of this sensor fibre configuration is tunnel temperature must be measured for fast fire detection (within 10 sec) even though DTS measure temperature using any channel.

3 DTS at site were connected ring configuration of optical communication for redundancy and all of 3 DTS data were transmitted to master station using OPGW (Optical Fibre Grounded Wire) of overhead transmission line. In master station one set of CTM and DRS was applied to calculate conductor, insulator, and metallic sheath temperature of entire route and estimate dynamic rating and emergency rating current in real time. The system starts operation in April 2005.

Until summer peak load season, all of the R-TAS™ data including tunnel hotspot, cable jacket hot spot and conductor hot spot distance and temperature were gathered and analyzed according to weather and load current and the results were described below.

Hot spot of tunnel and cable jacket

Using the optical fibre sensor installed on the ceiling of the tunnel, tunnel hot spot temperature and location were investigated and shown in figure 2.

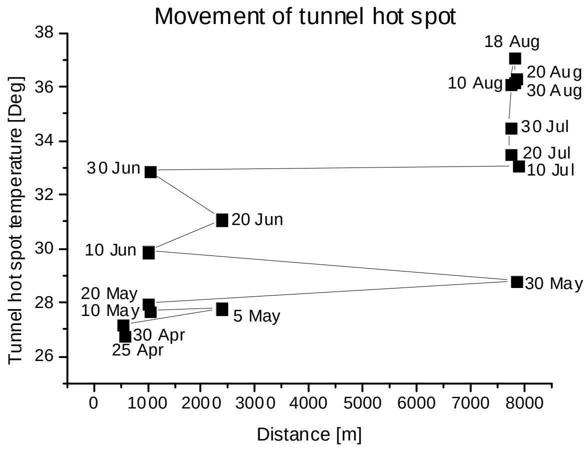

Fig. 2 Movement of tunnel hot spot

From figure 2, it should be noted that the tunnel hot spot location was changed with time. This is the reason why conductor temperature calculation should be done along the entire cable route [1].

In April, tunnel hot spot was located around 550m position which was the deepest tunnel area. The depth was about 32m. From May to June tunnel hot spot location was changed roughly 3 positions (2300m, 1000m and 7800m position) in turns which were shallow tunnel area. The depth was about 5m. In the hottest season from July to August, tunnel hot spot happened almost one area (7800m position) and maximum temperature was 37.1℃ on 18th August. The position had the characteristics that the distance to the near ventilation fans was the furthest position except deep tunnel area and also far from water hole. The hot area was the broadest than any other area (almost 200m). From the analysis, 4 areas of 2℃ higher temperature than others were selected to tunnel hot spot area and especially the area from 7700m to 7900m should be administrated carefully in summer. Cable jacket hot spot location was very similar to that of tunnel hot spot. Just like tunnel hot spot, the area from 7700m to 7900m was selected higher temperature area in summer. In order to find out the main factors to hot spot temperature, weather parameters such as maximum air temperature on earth and rain fall and load current of transmission cable circuits were investigated and shown in figure 3 and 4.

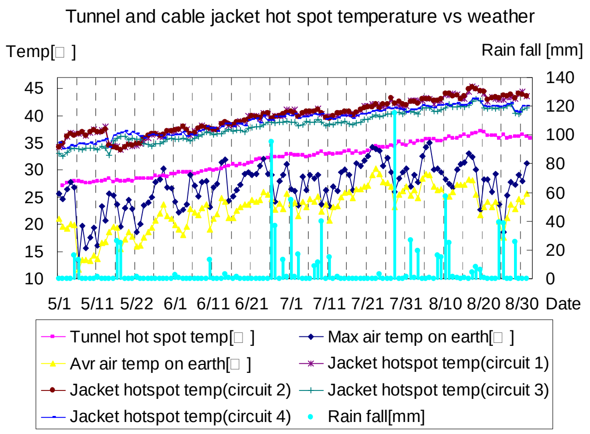

Fig. 3 Hot spot temperature vs weather

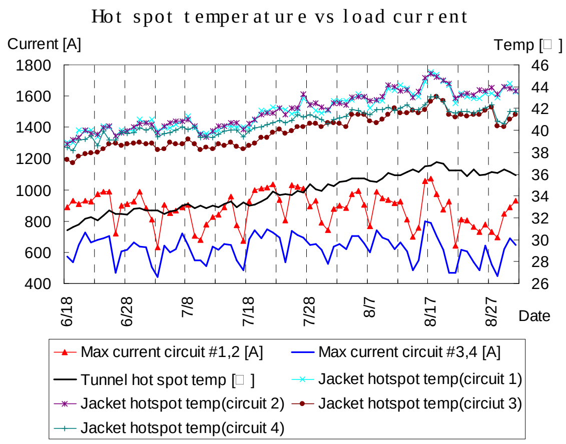

Fig. 4 Tunnel hot spot temperature vs load current

The overall pattern of tunnel and cable jacket hot spot temperature tended to increase by about 1□ in every 10 days from 1st May to middle of August and record high of hot spot temperature and the day during summer in 2005 were shown in table 2.

From figure 3 and 4, the overall increase and decrease pattern of tunnel and cable jacket hot spot temperature was affected by air temperature on earth more than load current but the affection seemed to lag about 10 days behind the weather and small temperature variation was affected by load current more than air temperature. It should be noted that small variation of jacket hot spot temperature had much sensitive to load current variation than tunnel hot spot temperature.

Table 2 Record-high values in summer 2005

Item		Date	Value
Air temp. on earth	Max	6, Aug	35.0□
	Avr	5, Aug	29.3□
Load current	Max (Circuit 1, 2)	17, Aug	1071 A
	Avr (Circuit 1,2)	17, Aug	807 A
	Max (Circuit 3, 4)	16, Aug	800 A
	Avr (Circuit 3,4)	17, Aug	557 A
Tunnel hot spot temperature		18, Aug	37.1□
Cable jacket hot spot temperature	Circuit 1	17, Aug	45.3□
	Circuit 2	17. Aug	45.2□
	Circuit 3	18, Aug	43.1□
	Circuit 4	18, Aug	43.1□

One interesting result was that rain fall had influenced very little in short time being from the results of figure 3. Especially although rainy season from end of June to early July dropped maximum and average air temperature on earth and load current was smaller than before and after, tunnel hot spot temperature did not dropped but increased very slowly. These phenomena could be explained that the materials for example soil, concrete of tunnel wall and tunnel air had so high thermal capacitance that the influence appeared very slowly.

From the results of figure 3 and 4, the load current of cable circuits also affected tunnel hot spot temperature very cumulatively.

In order to investigate the relationship between hot spot temperature variation and load current during short time being, the one day trend was analyzed and shown in figure 5 and 6.

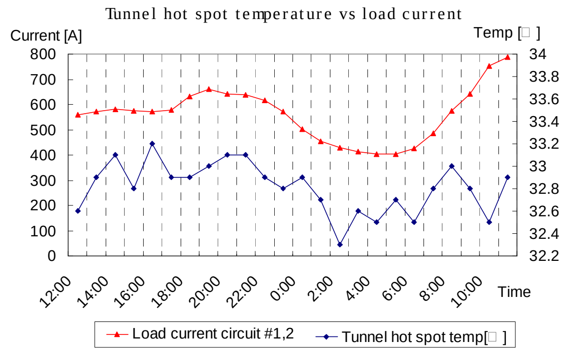

Fig. 5 Tunnel hot spot temperature vs load current (One day trend)

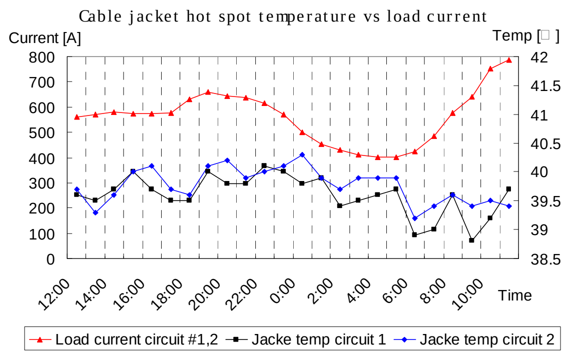

Fig. 6 Cable jacket hot spot temperature vs load current (one day trend)

Tunnel hot spot temperature variation was within 1 □ and cable jacket hot spot temperature variation was about 2.2□ during one day. The load current did not seem great effects to tunnel hot spot temperature during 1 day,

One important thing of cable jacket hot spot one day trend was that the affection of load current appeared about 4 ~ 5 hours later from figure 6.

From the application results, it was revealed that all of the joint surface temperature was always lower than that of cable jacket, so joint could not be thought as bottle-neck of rating current. This is because the tunnel area of cable joint is normally wider than that of cable in Korea. And thermal stability of joint was monitored and determined by temperature differences between R, Y and B phase. If the difference is within 5℃, we judge normal condition according to KEPCO standards and until now all of the joint have showed normal condition since April, 2005.

Cable conductor hot spot

Cable conductor temperature was calculated in real time using CTM applying thermal model based on IEC standard for the entire cable route [8, 9]. This is because normally hot spot location changes with time as shown in figure 2 and accurate calculation needs previous cable conductor, insulation, metallic sheath and cable /jacket temperature. The input parameters were load current and cable jacket temperature measured by DTS.

The conductor hot spot location was same position of cable jacket temperature and the record high temperature was appeared on 17th August for all 4 circuits and the values were 56.4℃, 56℃, 53.7℃ and 54℃ respectively. Overall increase and decrease pattern of cable conductor hot spot temperature was very similar to tunnel hot spot temperature and the relationship between conductor hot spot temperature and load current was investigated and shown in figure 7 and 8.

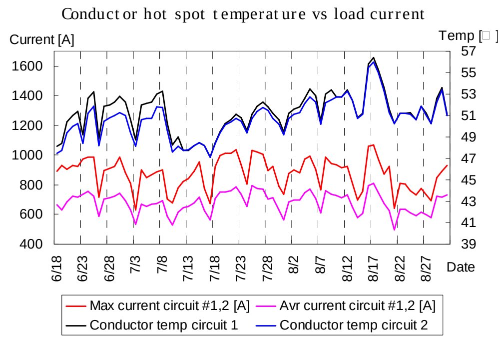

Fig. 7 Conductor hot spot temperature vs load current

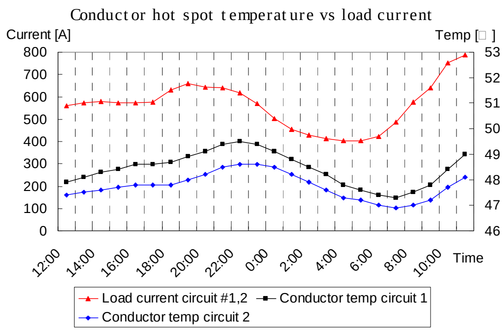

Fig. 8 Conductor hot spot temperature vs load current (One day trend)

From figure 7, cable hot spot temperature has affected directly to load current but the affection appeared about 2 ~ 4 hours later from figure 8.

Dynamic rating current analysis

Dynamic rating current during 2,4,8,12,24 and 48 hours was estimated at conductor hot spot applying DRS system. During summer, minimum dynamic rating current occurred on 17th and 18th August and the results of circuit 1 were shown in table 3.

Table 3 Minimum dynamic rating current in summer 2005

Item			Value [A]
Continuous rating current			1029
Dynamic Rating Current	Conductor Temperature: 85℃	2 hours	1163
		4 hours	1148
		8 hours	1133
		12 hours	1125
		24 hours	1119
	Conductor Temperature: 95℃	2 hours	1328
		4 hours	1298
		8 hours	1265
		12 hours	1249
		24 hours	1235

From the application results, continuous rating current had enhanced margin of 5.8% and 4 hours dynamic rating current of conductor temperature 85℃ showed 18.3% enhanced margin compared with conventional rating current.

Bukbusan-Nambusan project

Bukbusan-Nambusan transmission line consists of 3 circuits of 22 c-km long 345kV oil-filled cable and laying condition is tunnel. The outline of the transmission line is shown in figure 9.

Fig. 9 Bukbusan-Nambusan transmission line

The applied R-TAS™ system is composed of two master stations in main monitoring room in Bukbusan substation and Nambusan substation respectively and total 6 DTS systems in local tunnel site and two sets of CTM and DRS. The system starts operation in July 2005.

From summer in 2005 to summer 2006, record-high hot spot temperatures were shown in table 4.

Table 4 Record-high hot spot temperature

Item		Date	Value
Air temp. on earth	Summer 05	14, Aug	32.8℃
	Summer 06	08, Aug	34.5℃
Tunnel hot spot	Summer 05	17, Aug	44.9℃
	~ Winter 05	08, Dec	44.8℃

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temperature	~ Summer 06	24, Aug	46.1□
Cable jacket hot spot temperature	Summer 05	17, Aug	51.4□
	~ Winter 05	08, Dec	54.5□
	~ Summer 06	15, Aug	53.4□
Conductor hot spot temperature	Summer 05	17, Aug	64.3□
	~ Winter 05	08, Dec	66.6□
	~ Summer 06	15, Aug	62.0□
Continuous rating current	Summer 05	17, Aug	869.6 A
	~ Winter 05	08, Dec	871.6 A
	~ Summer 06	24, Aug	844.5 A

The high temperature shown in 8th Dec resulted from high load current in winter.
On the other hands the rating current of Bukbusan-Nambusan cable was designed based on tunnel hot spot temperature of 40□ but actual temperature showed much higher than the temperature so the system estimated continuous rating current should be de-rate to minimum 844.5 A which is 12.5% de-rated value than designed rating current.
From this application results, tunnel cooling system will be applied in this transmission cable line in 2007.

INTELLIGENT POWER CABLE SYSTEM

The extension of R-TAS™ system accelerated the development of optical fibre composite power cable and joint which had advantages for R-TAS™ to monitor duct and to analyze conductor temperature more precise.
Figure 10 shows optical fibre composite power cable and pre-molded joint (OP-PMJ).

Fig. 10 Optical fibre composite power cable and joint

The embedded optical fibre in optical fibre composite power cable are not only temperature sensor but also communication media of monitoring system so optical fibre composite power cable can transport both energy and information having a temperature sensor. Therefore the cable system was named intelligent power cable system.
The first monitoring system applying optical fibre composite power cable in Korea was installed between Gwangpyung and LS Cable factory in August 2005.
Intelligent power cable system applied in Gwangpyung - LS Cable line concentrated on monitoring the characteristics of cable system itself in order to assure maximum reliability of power cable system. The system has a function of general monitoring, R-TAS™, on-line PD monitoring and suppression of sheath circulating current. Table 5 shows the monitoring items of intelligent power cable system

Table 5 Monitoring items of intelligent power cable system

Items		Functions	Method
CABLE & JOINT	Temp.	-Sheath temperature monitoring -Duct temperature monitoring -Hot spot detection -Fire detection	DTS
	Temp. analysis	-Conductor temperature monitoring	CTM
	Rating current	-Estimation of continuous rating current & emergency rating current	DRS
	Partial discharge	- Early detection of cable & joint insulation failure	On-line PD System
	Sheath circulating current	-Suppression of sheath current →Increase rating current	Suppression unit
ETC	Security	-Illegal entrance into facilities	Proximity Switch Photo Sensor
	Accident	-Early detection for abnormal situation -Safety for entrants and facilities	Gas sensor -O_2, -CO, -CH_4
	Control	-Management of relayed control •Gas→Ventilation Fan (ON) •Fire→Ventilation Fan (OFF) •Water → Pump	Control with Relay. •Pump, •Ventilation Fan •Light

From the application of intelligent power cable system in Gwangpyung – LS cable transmission cable, typical metallic sheath distributed temperature could be aquired and shown in figure 11. It has been revealed that there were 3 hot spot in Gwangpyung transmission line which represented A, B, and C in figure 11. In order to find out the reason of these hot spots, more detailed investigation was carried out. Through the investigation, we could find out that heat pipe lines were installed near the hot spot point A and B and hot spot point C was the interface between duct and tunnel.

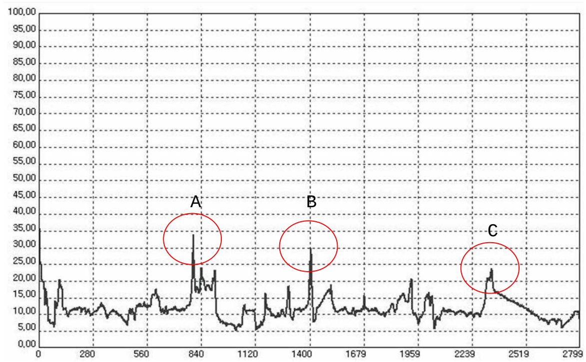

Fig. 11 Typical metallic sheath distributed temperature

The designed rating current of this cable line is 562 A which is based on IEC standard. When calculating rating current, ambient temperature is assumed to 25□ in duct and 40□ in tunnel in Korea.
After operating Gwangpyung monitoring system, we could find out that rating current of 562 A is very dangerous because of heat pipe near the power cable.
On the basis of measured temperature, rating current should be de-rated as 502 A. This value can be changed if data acquisition period is longer than now.
But without this monitoring system, operator may apply more than 502A and this may lead to power cable failure.

CONCLUSION

From application results of R-TAS^{TM} system in Shinyangjae-Gwachon project and Bukbusan-Nambusan project and Gwangpyung-LS cable project of intelligent power cable system, following things could be found out.

1) The continuous rating current of 345kV oil-filled cable line in Shinyangjae-Gwachon had enhanced margin of 5.8% compared with designed rating current.
2) Because tunnel hot spot location was changed with time, conductor temperature calculation should be done for entire cable route.
3) The overall pattern of tunnel hot spot temperature was affected by weather and seemed to lag about 10 days behind air temperature on earth.
4) The overall increase and decrease pattern of cable jacket and conductor hot spot temperature was similar to that of tunnel, but small variation of the temperatures was directly affected by load current.
5) Daily temperature variation of cable conductor and jacket hot spot lagged about 2 ~ 5 hours behind load current variation.
6) From the R-TAS^{TM} operation results in Bukbusan-Nambusan project, maximum tunnel hot spot temperature was 46.1□ which was much higher than designed value. So, continuous rating current should be de-rated by 12.5% and because of this results tunnel cooling system will be applied to the transmission cable line in 2007.
7) Intelligent power cable system applying optical fibre composite power cable and joint was successfully installed in August 2005.
8) The rating current of Gwangpyung cable system should be de-rated owing to the heat pipe near the cable.

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GLOSSARY

R-TAS^{TM}: Real-Time Ampacity Estimation System
DTS: Distributed Temperature Sensor
CTM: Conductor Temperature Monitoring Module
DRS: Dynamic Rating System
PD: Partial Discharge