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RESEARCH AND APPLICATION OF ACTIVE LIGHTNING PROTECTION TECHNOLOGY

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1. INTRODUCTION

The conventional passive lightning protection mode depending on fixed lightning rods, overhead grounded wires, arresters and SPDs couldn't fit for the demand in practice gradually. Therefore, it is necessary to explore an available and optional way that could enhance and improve them.

Based on Intelligent Control Technology and combined with lightning detection, the Active Lightning Protection (ALP) was researched. Active Lightning Protection means carrying out preventive measures in advance according to the real time lightning tracing information. It combined protection with lightning detection, and is different from the passive lightning protection mode. The ACTIVE mode more emphasizes the dynamic measures before potential hazards but not just waiting to be stroke. Accordingly, the ALP could be applied to many important industries and critical fields.

2. LIGHTNING HAZARDS TO ELECTRIC POWER AND COMMUNICATION SYSTEM

Electricity is modern society's most convenient, useful and important form of energy. Without it, the present social infrastructure would not at all be feasible. Furthermore, we also couldn't imagine our working and living without communication system and electronic devices nowadays. The more our life depends on electric power, communication, and electronic systems, accordingly, the more frequent threat of lightning hazards will become. Furthermore, the more serious destructive consequence would be than ever before.

2.1 Lightning hazards to Power Grid

Lightning is a significant cause of electric power system fault. It is well known that typical Electric Power System includes power plants, power grid (power network) and power consumers. And the power grid consists of transmission network and distribution network.

Lightning, especially CG lightning could damage many important components of the grid such as transmission lines, distribution lines, substations and so on.

(1) Transmission network

As a primary part of Power Grid, transmission and distribution lines are mostly exposed, covering long distance and large areas. The character greatly increases their probability of suffering from stroke. Correspondingly, lightning is one of the main causes of transmission line trips, or outages in operation. Overhead grounded wires, lightning arresters or reduce the grounding resistance are ordinarily measure used to prevent lines from stroke or damage. Nevertheless, they still couldn't completely avoid the lightning effects on transmission lines that lead to fault because of the random character of lightning. It was consider that the higher voltage level transmission lines have fewer influence of lightning strokes because their higher insulation performance, however, the higher voltage level, the more risk when lightning stroke cause abnormal trip. It's serious when the recloser failed especially. Obviously, the power grid would suffer the great impact.

(2) Substations

When lightning strikes a phase conductor of transmission line, the current of the lightning stroke will encounter the surge impedance of the conductor so that overvoltage will be built up and propagate to the substation along the transmission line in wave form. This lightning incoming wave would damage the electrical equipments and facilities in substation. If the SPDs on the incoming lines did not sensitive or reliable enough, the whole station would be at risk of lost the inside microelectronic devices, control systems or information network, even lost all of its power. As an indivisible part of the power grid, a substation quit of operation would lead to dangerous and unpredictable consequence.

Similarly, the lightning hazards to important power plants could cause the load shedding, abnormal oscillation, frequency collapse or power network separation.

(3) System Stability

In respect of the most normal condition, the protective relaying system of power grid separate or disconnect those defective elements or faulty sections from the system automatically and selectively, acting on the circuit breakers for tripping action when a fault occurs. But in some cases, it would expand the fault area unexpectedly because of the power system is a complex and interconnected dynamic balance system. Studies reveal that more than 60 per cent of faults are caused by lightning during storm days include directly or indirectly.

Not only harm the individual components of system, indeed the main damaging effects of lightning are they destroy the dynamic balance of power system, harm to the stability of power grid indirectly and cause the serious effect subsequent.

2.2 Lightning hazards to Power Distribution System

The principal mechanism of lightning flashover on HV, EHV and UHV transmission lines are the shielding failure and the backstroke events due to direct stokes. For the lower high voltage and distribution lines, the induced voltage accompany strokes close to the line predominantly contribute lightning overvoltages. Studies reveal that in distribution system more than 80 per cent of lightning overvoltages are caused by induced overvoltages.

Lightning damages to the power distribution system are a serious problem to many utility-systems and account for the majority of consumer outages causing the highest expense in breakdown of distribution equipment. Inadequate lightning protection results in faults on distribution system that may cause through-fault failures of substation transformers. Pole-mounted distribution transformer failures caused by lightning have also been a longstanding problem on most of the systems.

2.3 Lightning hazards to communication and electronic system

The communications industry suffers from both of the problems above and must also deal with direct lightning strikes to facilities and communications infrastructure. Lightning is a major cause of electromagnetic interference that can affect all electronic systems in every field and industry. Besides direct strikes, the lightning hazards of electronic equipment also caused by their secondary effects.

Strike up to a kilometer away can cause transient overvoltages or surges on main power, data communication and signal lines. They can cause data loss and corruption in computers and equipment damage.

Modern equipment is costly to repair although this can be insignificant when compared to the secondary costs resulting from equipment downtime, lost production and the huge costs and time involved in correcting and re-instating corrupt data and systems.

3. ACTIVE LIGHTNING PROTECTION OF POWER GRID

All components of the power grid form an organic whole and maintenance the dynamic balance in operation. The system frequency, voltage, tie-line flows, line currents and equipment loading must be controlled and kept with limits determined to be safe. Lightning could damage transmission lines, distribution lines, substations, plants and so on. Furthermore, such hazard may lead to loss of system stability and uncontrolled separation of power network even threatens the whole electric power grid.

After researched for many years, peoples find many available measures to protect the power system from lightning hazards, but all these ways are limited and each of them have many immanent defects.

As above (Section 2.1), the partial or whole of power grid could loss of stability during thunderstorm and cause to large areas outage is possible, although such occurrences may be infrequent. For electric utilities the ability to prevent or minimize lightning damage on power system is of great importance. Many power utilities used lightning data in ordinarily practice, but we are more interest in the whole Grid's security under thunderstorm.

Thus, from the point of view of whole power grid lightning protection, Active Lightning Protection regards all parts of the electric power system as an integrated system. Its ACTIVE mode emphasizes the dynamic measures before potential hazards but not just waiting to be stroke.

Accordingly, the Active Lightning Protection System depends on real time lightning data and intelligent control, provides secure dispatching strategies and operation measures of power grid under the thunderstorm weather. And it tends to avoid the potential accidents rather than after them really happened.

3.1 Framework of Active Lightning Protection System

The ACTIVE concept is presented here and means more attention paid to the whole grid's safety. We consider that it's important to combine lightning information system with power grid dispatch system. Integrate real-time lightning data into power grid dispatching scheme, carry out more measures before faults occurred could reinforce the stability of grid and its resistance ability of lightning.

ALPS designed to aid Power Grid dispatching, combine real-time lightning data and the important grid steady state and transient state data, analysis and process them, gives optimal dispatching control decision, which could finally give the optimal dispatch strategy calculate by the ALPS according to the Foundation Dispatch Rule Library, to improve the system stability.

The system framework of ALPS is shown in figure 1.

3.2 Basic application mode

Figure 2 shows a basic geographical connection diagram of power grid. The (1)-(5) cases assume the lightning storms move trace from five different directions.

In CASE (1), the lightning storms move from the south to north, and tend to across the Line A-E-F. Because of the importance of this line for the grid, the ALPS would try to reduce the load in this line, and move those loads to Line A-D-F and Line A-B-C-F.

The grid would suffer minimal impact, if the line A-E-F failed with minimal load base on it. Oppositely, if the Line A-E-F fail when it full with important load, it could lead to instability of the whole grid more than this line it self. In practice, we need to analyze the lightning information combine with other important grid state data, and give dispatching strategy.

Similarly, in CASE (2), the lightning storm come from north to south, the ALPS system would gives optimal dispatch scheme to move the important load on Line B-C-F to the relatively secure Lines, namely the Line A-D-F and Line A-E-F.

These dispatching measures that carried out in advance would improve the grid stability. Furthermore, the system would guide repair crew, increase plant availability and rapidly locate and analyze faults.

3.3 Basic mathematical model and functional design

The primary principle of the decision system is first collect the kind of data, such as real-time lightning data, SCADA (Supervisory Control and Data Acquisition) system, GIS (Geographic Information System), Extremely Short-team Load Forecast information and some important steady and transient state data of the grid, and use intelligent control method to analysis and process them. And according to the setting constraint conditions and factors, gives the pretreatment dispatching control decision, aid to estimate the stability of the outcomes value, than adjust the value with the constraint condition, through iterative calculate optimal dispatching control decision, which could finally give the optimal dispatch strategy calculate by the ALPS combined with the Foundation Dispatch Rule Library.

Figure 3 shows the data process procedure of the ALPS Decision Module.

3.4 Dispatch intelligent decision module

The core of is ALPS Intelligent Control Center is Dispatch Intelligent Decision Module. We design it based on intelligent control technology. Figure 4 describes the primary process, calculation and output procedure with two array cells system. In practice it may be parallel processed as multidimension array cell, in the most case, the process would be more complex because of the outside limit parameter or factor.

3.5 Optimal dispatching control decision

According the preconditioning function, the Control Decision system's simulate pre-output value is $x_m(t+N\tau)$, define the moment t, the difference between system optimal output $x(t)$ and the preconditioning output value $x_m(t)$ is: $e(t)=x(t)-x_m(t)$.

At the point t, the preconditioning value could be adjusted from $x_m(t+N\tau)$ to $x_m(t+N\tau)=x_m(t+N\tau)+he(t)$, and when h>0, means the weight coefficient of the deviation. Through the formula $u(t)=u(t-N\tau)+\frac{1}{\eta}[r(t+N\tau)-x(t+N\tau)]\frac{\partial x(t+N\tau)}{\partial u(t)}$ and $\frac{\partial x(t+N\tau)}{\partial u(t)}=\frac{\partial x_m(t+N\tau)}{\partial u(t)}\approx\frac{\Delta x_m(t+N\tau)}{\Delta u(t-N\tau)}=\frac{x_m(t+N\tau)-x_m(t)}{u(t-N\tau)-u(t-2N\tau)}$ could deduce the optimal output.

3.6 Stability analyze

Base on the theory of system stability analyze, we could set the initialization:

$$E(t+N\tau)=r(t+N\tau)-x(t+N\tau).$$

According the initial condition from the theory above: $V(t+N\tau)=\frac{1}{2}E^2(t+N\tau)$

Combined with the formula $\Delta E(t+N\tau)=\frac{\partial E(t+N\tau)}{\partial u(t)}\Delta u(t)=-\frac{\partial x(t+N\tau)}{\partial u(t)}\Delta u(t)=-\frac{\partial x_m(t+N\tau)}{\partial u(t)}$ we could get formula $\Delta V(t+N\tau)=-\frac{1}{\eta}(E(t+N\tau)\frac{\partial x_m(t+N\tau)}{\partial u(t)})^2\bullet(1+\frac{1}{2\eta}\frac{\partial x_m(t+N\tau)}{\partial u(t)})^2)$

From above two formula, we could deduce: when $\eta>0$, $\Delta V(t+N\tau)\le 0$, the value of system stability could suffice the operation requirement.

4. ACTIVE LIGHTNING PROTECTION OF POWER DISTRIBUTION SYSTEM

As the power grid which covers several states is macro level of power network, the distribution network which services for a region or area is micro concept relativity.

Studies indicate that lightning is responsible for more than 70% of all faults on distribution systems during storm days. Roughly 75-80 per cent of these lightning faults are of a transient nature and lines can be reenergized on reclosing the breaker. And those faults couldn't restore by recloser could cause outage for a period of time.

Active Lightning Protection accord real time lightning detection data adjust the operation mode of distribution system to improve the power supply reliability and network safety.

The ALPS system applied in Distribution system tend to switch feeder line or additional power source that supply to important Loads or density center. It optimal the flow and avoid the path through the thunderstorm center in rule.

4.1 Auto-adjust coefficients

Auto-adjust coefficient on key point for a flow series is often useful for identifying variations. The Auto-adjust coefficient of a flow series could defined as $R_{xx}(\tau)=\frac{\sum_{t=\tau+1}^{T}x_t x_{t-\tau}}{T-1-\tau}$, in a multi-control process, the average coefficient of the flow series in dynamic state should be define as $\rho(\tau)=\frac{R_{xx}(\tau)}{R_{xx}(0)}$. Obviously, the ALP auto control foundation rule library should combine with the auto-adjust coefficients to real time operation data source on a certain unit process.

4.2 Real time load forecasting

It's necessary to forecasting the load in distribution system active lightning protection although it is beyond the scope of this paper. Real time load forecasting for short duration varying from a few minutes to 2-24 hours has been in prevalent by power utilities for normal system operation.

The following formula gives an ALP system statistical mode of distribution in lightning weather conditions:

$$P_r(a<x<b)=\int_a^b \frac{\exp(-\frac{1}{2}(x-\mu)^2 \big/ \sigma^2)}{\sigma\sqrt{2\pi}}dx$$

Active Lightning Protection should change operation state accord the important level and identity of the load when lightning is approaching.

Table 1 shows the operation data of a Local-Area ALPS in a power distribution network. The system integrated with a lightning detection sub system and service from 2003. The lightning data source comes from Tss928 local area sensor and a domestic lightning location network. And we find that the accuracy of the lightning tracking information is one of the most important factor limit the ALPS performance.

5. ACTIVE LIGHTNING PROTECTION OF COMMUNICATION AND ELECTRONIC SYSTEM

The Communication System described here is comprehensive. The communication system and electronic equipments were applied in every industry and field nowadays.

5.1 Inverse stroke and incoming lightning overvoltages wave

Under the direct stroke, a down conductors system and grounding system with ideal low value earth resistance would help the dissipation of huge lightning current. But the Earth Potential of the building's location will rise inevitable. In some lightning discharge conditions, the earth potential would raise up to a high value transiently, usually arrived hundreds of kilovolt, greatly exceed the level that electrical equipments and facilities could suffer. In most situations, the electrical equipments use the same working earthing system and protective earthing system. Moreover, bond all individual earthing systems. So the power frequency earthing and lightning protection earthing network use the same equipotential grounding system. When lightning discharge caused earth potential rise, the great voltage difference would damage the working electrical equipments and facilities within the building. Such case called inverse stroke. It is possible that the similar instance happened when lightning direct strike on the ground nearby the building.

Direct strikes on the incoming power lines of communication and electronic system, will cause lightning overvoltages wave on the lines. More than 75% of all field failures of electronic systems are caused by electrical overstress. According to the analysis and statistics, the total lightning accidents that caused by overvoltages enter from incoming power supply lines come to 70-80%. In the other word, lightning overvoltages from incoming power supply lines damage electronic equipments and communication systems became the main form of lightning disasters nowadays. The generally measure is installing SPDs on the lines. SPD was design for protecting against surge form many sources. Besides lightning, they include inductive kick from relays, solenoids, motors and power generating systems etc. All SPDs have a response time parameter, and before its action, there is a time delay. In many cases, as one of the most formidable natural forces, lightning is unpredictable and rapid. Frequently, the sensitivity of SPD is not enough to prevent lightning's huge and destructive energy after a period of time. It's the main reason that the electronic equipments equipped with SPDs still damaged by transient overvoltages in thunderstorm. Moreover, not only direct strikes, but nearby strikes, would induce overvoltages and surges on the incoming power lines. It is a very important source that the overvoltages and surges come from.

5.2 Basic Active protection mode and multi-target protection

The basic Active protection mode for communication and electronic system is isolating them form the outside power source in advance according to the lightning tracking information. ALPS would auto switch to inner backup power source, break down the outside source. Moreover, it parallel controls all important protection target in a region.

At first, the protection target could prevent from the overvoltages incursion from power supply lines when the lines had been switched off. In addition, the inverse stroke could be successfully avoided. Cutting off the incoming power source, the backup power source such as UPS and the equipments within the building would compose an independently system. There was no abnormal voltage difference in this independently system. Even if the lightning strike cause the earth potential rise, the situation would not alter, because earth potential and neutral point is a relative concept, if earth potential rise whole the independently system, it would maintain the normal voltage difference, and would not cause faults. Thus in an independently system without incoming source could prevent inverse stroke. So, switch to Backup Power Supply not only provide continuant Power Supply, but also prevent from the lightning hazards.

Multi-target protection means to control a number of important targets in a region. Each target has individual control scheme according its location and distance of thunderstorm. It would be far more complex than control a single target when control more than 100 targets. ALPS Process Center model would take charge this function.

6. CONCLUSIONS

The more our life depends on electric power, communication, and electronic systems, the more frequent threat of lightning hazards will become. Accordingly, the more serious destructive consequence would be. The conventional passive lightning protection methods couldn't completely fit for the demand at present. It's necessary to research and apply the Active Lightning Protection technologies to important industries and critical fields.

The paper described the ACTIVE mode of lightning protection which bases on intelligent control, combines lightning protection with lightning tracking and emphasizes the real time dynamic measures before potential hazards.

The Active Lightning Protection discussed in this paper provided an optional way that could improve the passive ones and would become a new available lightning protection approach.

7. REFERENCES

[1] HongGu, 2001: Modern Lighting Protection Technology, University of Electronic Science and Technology of China Publishing Company, P 118

[2] Guangrun Xie, 1997: Overvoltage of Electric Power System, China Hydraulic and Electric Publishing Company

[3] R.H.Golde, 1977: LIGHTNING, Vol 1. Physics of Lightning, ACADEMIC PRESS INC. (LONDON) LTD

[4] R.H.Golde, 1977: LIGHTNING, Vol 2. Lightning Protection, ACADEMIC PRESS INC. (LONDON) LTD

[5] E.P.Krider, Rise times of impulsive high-current processes in cloud-to-ground lightning, Antennas and Propagation, IEEE Transactions on Volume 48, Issue 9, Sept. 2000 Page(s):1442 - 1451

[6] E.P.Krider, On the chances of being struck by cloud-to-ground lightning, Power Tech Conference Proceedings, 2003 IEEE Bologna, Volume 3, 23-26 June 2003 Page(s):4 pp. Vol.3

[7] IEEE, Working Group on Estimating Lightning Performance of Transmission Lines. A Simplified Method for estimating lightning Performance of Transmission Lines. IEEE Trans.Vol. 4, April 1985, P:919～932.

[8] IEEE Working Group on Estimating Lightning Performance of Transmission Lines. Estimating lightning Performance of Transmission Lines II-Updates to Analytical Models [J].IEEE Trans. 1993, P 125～128.

[9] IEEE Working Group on Estimating Lightning Performance of Transmission Lines. Design Guide for Improving the lightning Performance of Transmission Lines .IEEE Standards PAR 1243, Draft 9, February 1992, P919～932.

[10] Zipse, D.W, Lightning protection systems: advantages and disadvantages, 1994

[11] Industry Applications, IEEE Transactions on, Volume: 30, Issue: 5, Sept.-Oct. 1994.

[12] Durham, M.O, Durham, R.A, 1995: Lightning, grounding and protection for control systems, Industry Applications, IEEE Transactions on, Volume: 31, Issue: 1

[13] Forsey, M., Protection against the effects of lightning, Integration of Earthing Practices (Digest No: 1997/307), IEE Colloquium on 18 Nov. 1997, Pages: 7/1 - 7/5

[14] E. P. Krider, M. A. Uman, “A review of natural lightning: Experimental data and modeling,” IEEE Trans. Electromagn. Compat., vol.EMC-24, pp. 79–112, May, 1982.

[15] E. P. Krider, R. C. Noggle, “A gated wideband magnetic direction-finder for lightning return strokes,” J. Appl. Meteor., vol. 15, pp. 301–306, 1976.

[16] A.Urbeta, 1986: "Sensitivity Study to EOS/ESD of Bipolar Integrated Circuits" in Proceeding of EOS/ESD Symposium, 1986 EOS/8, P 214

[17] Marshall, M.W. andAngeli, B.P, 1996: Establishing a lightning protection evaluation program for distribution and subtransmission lines, Rural Electric Power Conference, Papers Presented at the 39th Annual Conference.

[18] Forsey.M, 1997: Protection against the effects of lightning, Integration of Earthing Practices (Digest No: 1997/307), IEE Colloquium on 18 Nov. 1997, P: 7/1- 7/5

8. FIGURES AND TABLES

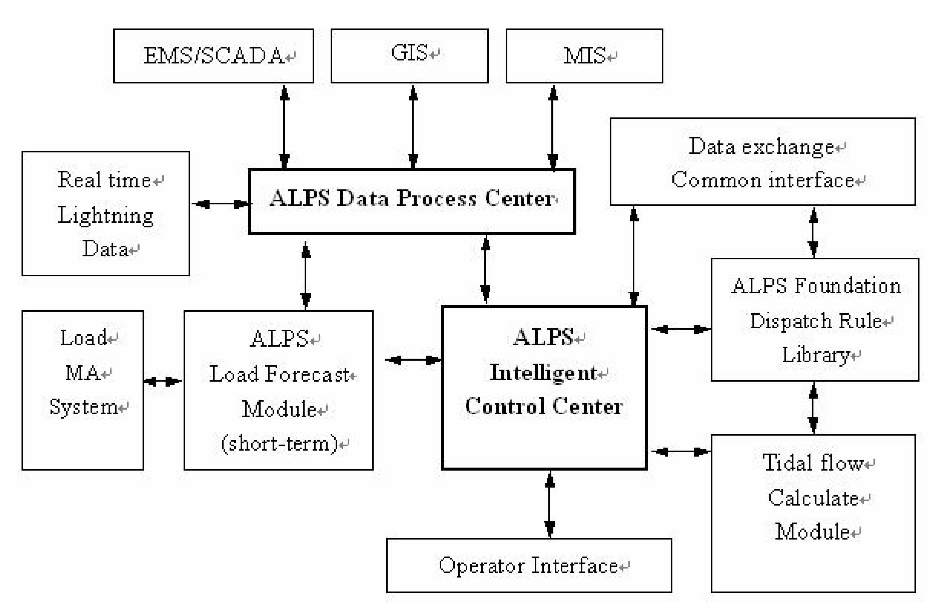

Figure 1. Framework of ALPS

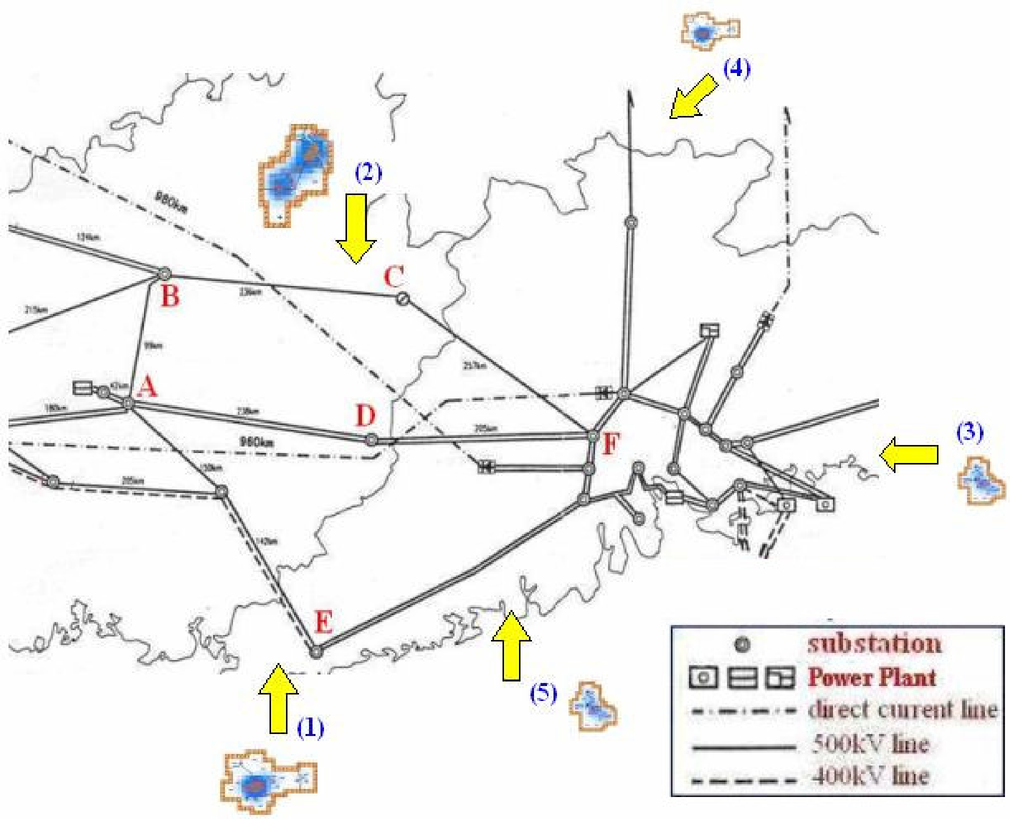

Figure 2. A Basic Power Grid Connection Diagram
Note: (1)-(5) are lightning storms moving trace in five directions

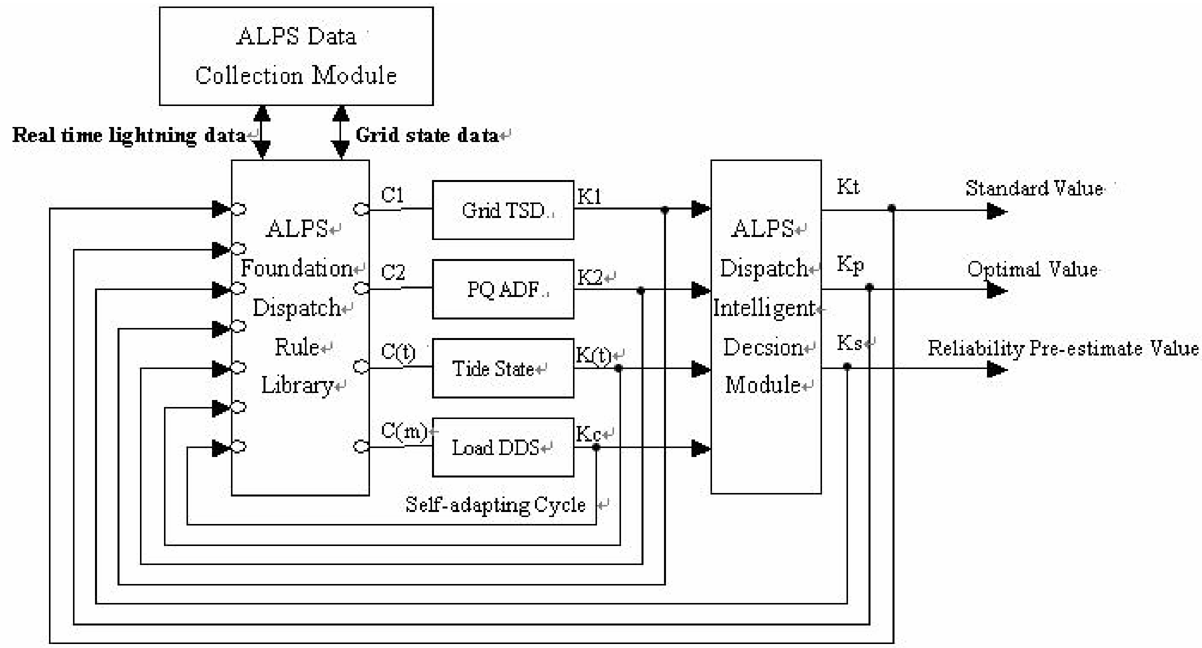

Figure 3. Data process procedure of the ALPS Decision Module

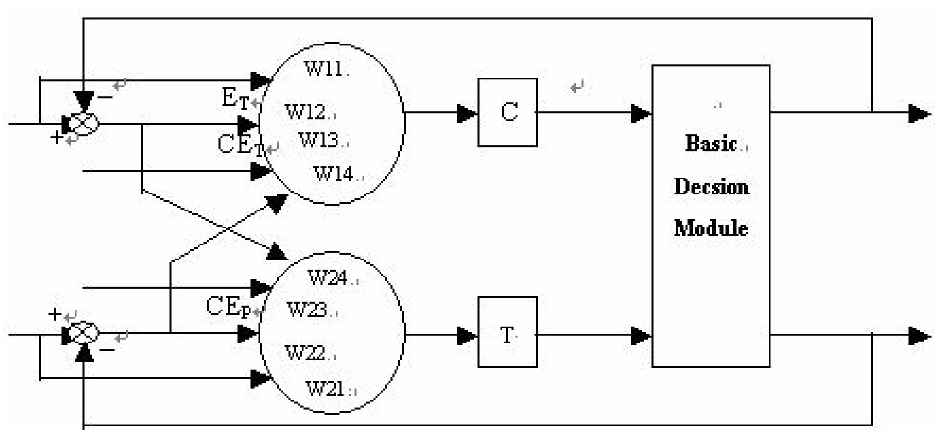

Figure 4. Basic Twice Data-Cell Process mode

Table 1. Local-Area ALPS operation data of a distribution network

	2003	**2004**	**2005**	**2006**	**2007**
Trip caused by lightning	1417	1325	1383	1257	1405
Auto recloser failed number	313	308	297	263	321
ALPS avoid key load outage	215	203	176	218	223