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Power Loads Fast Transfer & Control of Dynamic Lightning Protection of Smart Grids

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***Abstract*—Lightning disturbance is the one of the main reasons which leads to power grid outages in China, especially in summer heavy load situations. At the same time, the power loads in most regions are increasing rapidly in recent years. As each power grid includs big number of lines and devices, the quantity of failures is considerable. An individual fault sometimes leads to a larger scope accident. With the integration of real time lightning detection, the power loads fast transfer strategies was researched and the control system was developed. The paper described the advantages and limitations of such a Smart Grid power loads adjust solution based on the lightning tracking. The power loads fast transfer & control of Dynamic Lightning Protection, which is applied to reduce the lightning-caused outages, is also discussed in the paper.**

Keywords—Lightning Detection; Power Loads; Dynamic Lightning Protection; Smart Grids

I. INTRODUCTION

In the recent 12 years, the power outages related to lightning are more than 50 percent in China. In those electric power grid load centers, such as a city or an area with numerous manufactures, a lightning-caused fault would impact a large number of customers in a small geographic area.

As the second largest power load center in China, the load perk of Suzhou reached 25,800 MW. A ±800kV long range HVDC line (full length 2000 km) is one of the important power sources of the regional power grid. Any tiny disturbances would causes considerable side effects. In the north part of Suzhou, a large steel production base is located. In the south and east part of Suzhou, there are a great number of electronic devices or chips production factories. Thus, a reliable power grid is essential to ensure the continuous power supply.

Due to complicate structure and big scale, the improvement of lightning performance of each individual device cannot satisfy the reliability requirement of the whole system. On the other hand, many devices of important users are sensitive to the power supply. Most lightning-caused nonpersistent faults on power lines could be eliminated by circuit breakers reclosing or relay protection system, and normally will not lead to a long-term interruption. However, even the fastest reclosing cannot satisfy the requirement of these sensitive users.

As a system-level protection mode, the Dynamic Lightning Protection (DLP) has been a superior solution on power grid/Smart Grid reliability. With the integration of real time lightning detection, the power loads fast transfer strategies based on DLP mode and the control system were researched and developed.

II. OPERATION MODE OPTIMIZATION OF DYNAMIC LIGHTNING PROTECTION

Operation mode of power grids/Smart Grids means the real time network topology structure of an operating power grid, determined by the combination of circuit breakers' (or isolation switches') actual positions. The control of operation modes is the basic measure to change the power current direction and network circuit/loop.

Fig. 1 shows a part of a power grid which includes six 220kV substations and one 220kV power plants. Each of them has two 220kV Buses (Bus I and Bus II), and each has a circuit breaker between two Buses (Bus coupler circuit breaker).

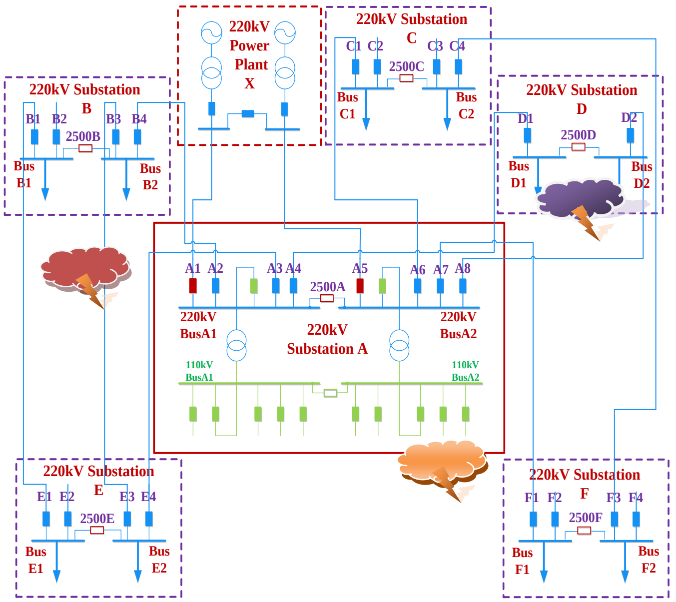

Fig. 1. Connection diagram of a part of 220kV grid

Through the close/open of Bus coupler circuit breakers (2500A, 2500B, 2500C, 2500D, 2500E, 2500F) and/or line circuit breakers (A1-A8, B1-B4, C1-C4, D1-D2, E1-E4, F1-F4) which located in each substation, the Buses can form a loop or a combination of loops. The operation modes of a power grid/Smart Grid can also be switched and adjusted through the switching of related circuit breakers.

The essence of operation mode adjustment is to change the circuit or network configuration of a power grid by switch a series of switching devices/elements (e.g., circuit breakers, isolation switches).

The changing of operation modes can alter the power flow distribution and affect the system security. The arrangement of operation modes is determined by economy and reliability, and also must consider the security limited factors, e.g., transformers capacity, lines transmission capacity, CB breaking capacity, relay protection coordination. Operation modes will be switched because of overhaul, overload, emergency or other requirements.

Accordingly, after stability estimation and optimal power flow calculation, the power grid could be switched to a secure mode which is selected from a Foundation Dispatch Rule Library (FDRL).

Fig. 2 shows the Connection diagram of the substation A.

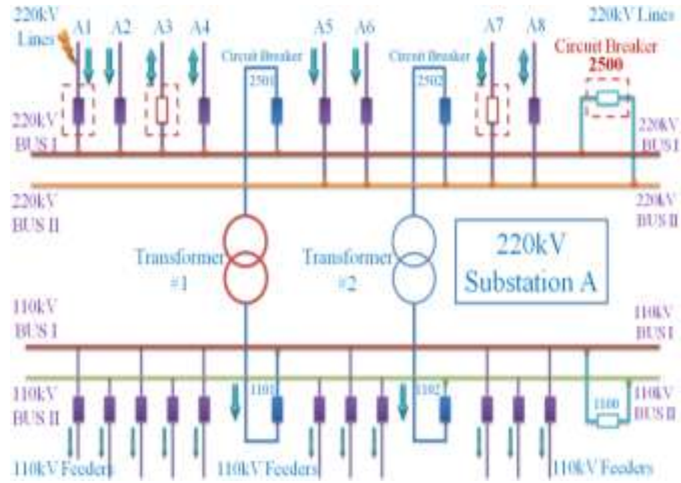

Fig. 2. Connection diagram of 220kV substation A

The 220kV substation A shown in Fig. 2 has eight 220kV lines (A1-A4 connected to 220kV Bus I, A5-A8 connected to 220kV Bus II). Each 220kV line is connected to a 220kV Bus in another substations or the power plant, as shown in Fig. 15.

When real time lightning tracking module triggers the operation mode action, the system will automatically close (in Auto-control Mode) the CB 2500B, CB 2500D, CB A3, CB A7, or submit the strategies (in Manual-control Mode), if system stability calculation satisfy the security condition. Then the substation D will be operated in loop mode, and fed by a loop which contains two power plant incoming lines (from power plant X) and more external power sources (from substation C (C2-C1-A6) and from substation F (F2-F1-A7)). The reliability of substation A and substation D will be improved.

III. Power Load Transfer & Control of Dynamic Lightning Protection

A. *Power Load Transfer & Control*

Power load transfer actually means to alter the power source or supply route of the loads. The principle of power load transfer of Dynamic Lightning Protection is to limit the Cumulative Effects and to prevent Cascade Effects.

Fig. 3 shows a basic mode of load transfer in an 110kV substation.

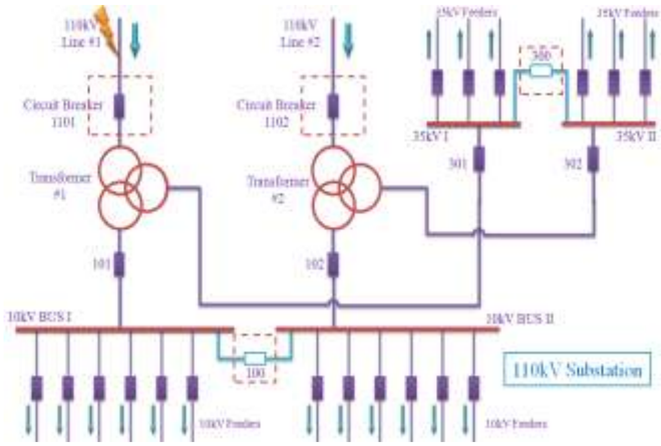

Fig. 3. Connection diagram of an 110kV substation

The 110kV substation shown in Fig. 3 contains two transformers, each supplied by an 110kV incoming line. If a lightning stroke causes the l10kV line #1 to trip and fail to reclose, the transformer #1 will lose power. To ensure the continuous power supply, the relay protection system will automatically open the CB 101, CB 301, and close the CB 100, CB 300 at the same time. In Some cases, the CB 1102 will overload rapidly in the moment. Then the CB 1102 may trip too, because of the trigger of relay overload protection. Thus, the whole substation may lose power because of a lightning stoke.

According to the Dynamic Lightning Protection, the loads located in the grid sections threaten by lightning stroke, should be transferred and balanced.

For the basic model of Fig. 3, the loads which are fed by 10kV Buses can be transferred by a Dynamic Lightning Protection Sloution (automatically or manually) through the following methods: (1) converting a part of 10kV feeder lines to incoming supply lines through the 10kV loops, (2) closing the CB in the other side of loop and open the CB in this side, transfer the loads to other substation, (3) switch the Microgrids (if available) which connected to the feeder lines.

The larger scale loads transfer of Dynamic Lightning Protection will also relate to power flow calculation and grid stability estimation. The principle is same, which is to limit the Cumulative Effects and prevent Cascade Effects.

B. *Stability constrained optimal power flow*

The prerequisite to maintain the balance of a power grid in steady-state operation is the generation equals to the load demand plus the losses. In a Smart Grid, we have more flexible and adjustable methods to enhance the stability and robustness at the same time.

The optimal power flow is an appropriate method to identify the control actions needed to ensure the stability of real-time operation, because the power flow problem can be formulated as a set of nonlinear algebraic equations.

It requires real time lightning tracking data to estimate the dynamic transient stability under a lightning caused disturbance, as well as the dynamic actions related to operation mode switching and load transfer.

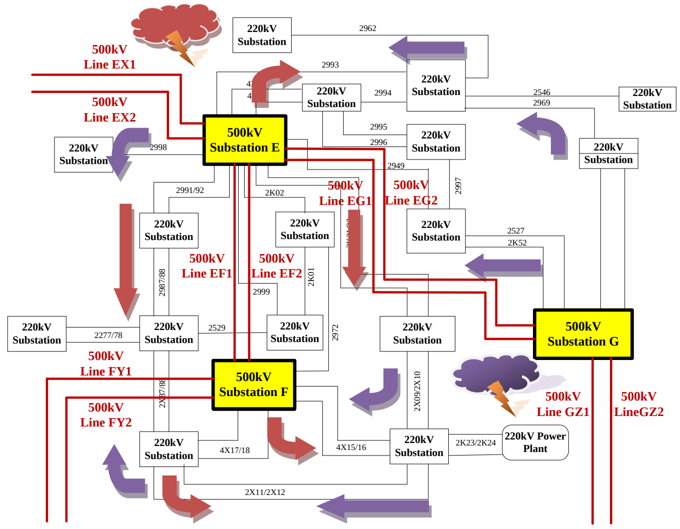

Fig. 4. Connection diagram of a part of a power grid

Fig. 4 shows a section which consists of three 500kV substations and several 220kV substations. Its power loads are about 3,000MW and in normal operation modes, about 40% loads are supplied by local power sources and about 60% by external power sources. Similarly, it will exchange loads with the grid section A, or enhance the interconnection with each other when they both face the lightning threat, in order to provide enough redundancy in emergency.

Therefore, it's important to optimize the power flow and ensure the system voltages, frequency, generator outputs, and line current carrying capacity within the safe limits at the same time.

To realize the local power loads fast transfer & control, the stability constraints within an optimal power flow incorporation model of a certain grid structure will be determined by the following procedures:

(1) Lightning storm tracking and alert triggers for main grid, (2) Main grid real time state estimation, (3) Traverse foundation library and match optimal control strategy, (4) Power flow calculation and stability estimation.

The above are four typical procedures mainly focusing on the operation mode selection which based on stability constrained optimal power flow. However, a Smart Grid may be combined with renewable power sources which are more be volatile, thus another constrained factor should be considered.

Combined with the lightning threat influence constrained condition, the dynamic stability constrained optimal power flow is a nonlinear semi-infinite optimization problem that includes algebraic constraints and differential equation. Thus, applied in the DLP mode, the considered optimal power flow includes the pre-fault power flow equations, parameters bound on generators, buses and lines, transient swing equations for all the machines of the system as well as the dynamic stability bound on the angle of the single equivalent machine. The objective function to be minimized is the stability coefficient as a result of adjusting controllable units.

IV. General State Estimation Based on Lightning Information

General state estimation based on lightning information includes two aspects: (1) employing the Smart Grid operation data sources to accurately acquire and monitor the system real time operation state, (2) utilizing these achieved state data and combining them with lightning tracking information, to estimate the Smart Grid dynamic lightning performance and to analyze/predict the system stability, and (3) evaluating the rationality of power load transfer & control strategies.

Fig. 5 shows the framework of a Smart Grid general state estimation model which is integrated with lightning information.

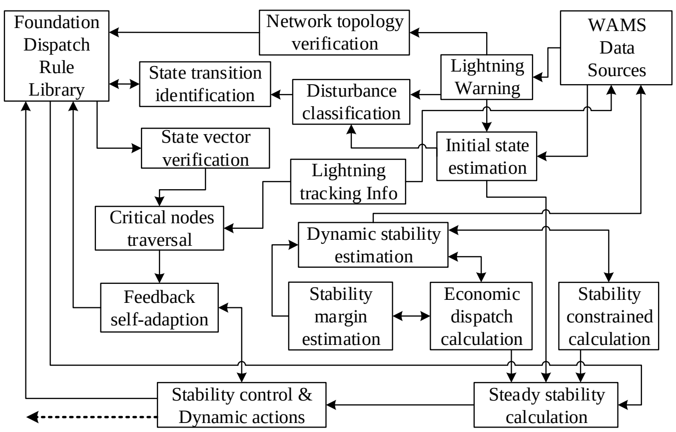

Fig. 5. General state estimation model

For the general state estimation based on WAMS, a power grid/Smart Grid can be modeled as a set of differential algebraic equations:

$$\begin{cases} \dot{x} = f(x,y) \\ z = g(x,y) \\ h(x,y) = 0 \\ \dot{d} = l(x,y) \end{cases} \quad (1)$$

where *f* is the nonlinear function of state transition, *h* is the nonlinear observation equations, *g* is a set of algebraic equations. *g* is formulated as a nodal equation with a admittance matrix. The *x*, *y* of a given system can be solved from function *g*. *d* is defined as the per-estimate state of a potential lightning disturbance.

Combined with numerical integration scheme, the equation (1) could be discretized and converted to algebraic form. The process can be integrated as follows.

According to a lightning disturbance factor *d* deduced by transition predict matrix, predicted state could be calculated based on the initial state:

$$\begin{aligned} X_k &= \chi_k = [\chi_k^0, \chi_k^1, \ldots\ldots, \chi_k^{2n}] \\ X_{k+1} &= X_k + \Delta t \cdot f(X_k, y_k) \\ p_{k+1}^* &= \hat{X}_{k+1} W \end{aligned} \quad (2)$$

Calculate y_k^* by solving

$$g(p_k^*, x_k^*, y_k^*) = 0 \quad (3)$$

Calculate the predicted state value p_{k+1}^- shown in (4):

$$p_{k+1}^- = p_k + \Delta t \cdot [\, f(p_k, x_k, y_k) + f(p_{k+1}^*, x_{k+1}^*, y_{k+1}^*)] \quad (4)$$

Combining with the lightning disturbance pre-estimate value $\dot{d}$, and substituting the p_k^- as initial state, the predicted covariance of the measurement can be calculated. And the cross-covariance of the state measurement D_{k+1} is given as follows.

$$\begin{aligned} X_{k+1}^- &= \chi_k^- \\ Z_{k+1}^- &= h(X_{k+1}^-, x_{k+1}^-, y_{k+1}^-) \\ D_{k+1} &= X_{k+1}^- [Z_{k+1}^-]^T D_k \end{aligned} \quad (5)$$

After calculating the filter gain matrix F_{k+1}, the verified state value p_k and final state covariance matrix V_{k+1} can be given as follows.

$$\begin{aligned} F_k^- &= C_k S_k^{-1} \\ p_k &= p_k^- + F_k [z_k - Z_k^- D_k] \\ V_{k+1} &= V_k^- + F_k S_k [F_k]^T + D_k^- \end{aligned} \quad (6)$$

If the Δt it is not sensitive enough, the outcome is prone to divergence. At the same time, WAMS data acquisition efficiency is important to the implementation of state estimation.

V. Application Sample

A project application Sample were applied and integrated in the Dynamic Lightning Protection System of Suzhou Smart Grid, which operates in the Power Grid Dispatch & Control Center. At the present stage, loads fast transfer & control module is a part the exemplary project in Suzhou, China since 2016.

Table I shows the data of SR time, AI time and RL Value in 32 local lightning-caused permanent fault events (with/without DLP loads fast transfer & control - LTC). In the table, SR time is average System restore time which means the duration of a system restore to the initial steady state; AI time is Average interruption time which means the duration of a terminal node outage; RL Value is the estimation of rescued power loads values.

TABLE I. System Restore and Average Interruption Time

	Remote trip event without LTC	**Remote trip event with LTC**	**Terminal trip event without LTC**	**Terminal trip event with LTC**
SR time	36 min	23min	19 min	15 min
AI time	N/A	N/A	27 min	11 min
RL Value	N/A	80MW	N/A	110MW

At present, there still inherent limitaions and disadvantanges.

1) Unavailable for individual devices

It is unavailable or has no effects to an individual device. The conventional protection measures of every device are still essential.

2) Risk and cost of the extra control actions

The extra control actions would bring more risks to an operating power grid. The necessity must be calculated and evaluated before every action to be implemented.

3) Smart Grid construction proceeding

In general, Smart Grids are still under construction. Many dynamic control methods, which could improve the system performance, are still unavailable.

VI. Conclusion

In this paper, the power loads transfer & control, the operation mode optimization and general state estimation based on real time lightning detection are presented. The power loads fast transfer & control of Dynamic Lightning Protection, which discussed in the paper, would be an available solution to balance the regional power grids loads and to reduce the lightning-caused outages.

The further application of real time lightning data could improve the global lightning performance of the power grids/Smart Grids.

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