Online Power Assessment Based on Risk Theory

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Abstract- Power system is approaching its limits due to the deregulation of power industry and unavailability of new transmission corridor. However power system security assessment is carried out and the operating limits are set according to the given contingency list which might happen in very rare frequency. In other words, the frequency of fault occurrence and the risk of blackout is varied when the operating condition (load level, status of power equipment, and weather) changes. How can we do the security assessment based on the operating condition to get the best equilibrium between the security and the profit is the focus of this paper. The idea of risk based on-line power system security assessment is suggested. A precise calculation method of average failure rates of components is presented. Besides, operating condition-based failure rates of components are also analyzed systematically in the paper. The Monte-Carlo simulation demonstrates the viewpoint of the paper.

Indexed Terms- security assessment, risk, failure rate, false trip of protection, power systems.

I. INTRODUCTION

The operating environment of power system is becoming increasingly competitive. The introduction of new technologies (HVDC, FACT, etc) makes the dynamic behavior of the system become much more complicated. The deregulation of power industry makes the system approaching its limit. Moreover, power grid interconnection makes the large-scale blackout occurs more frequently, which result in incredible economic loss. All these factors present the need for security assessment, which can clarify the on-line security status of power system, give early warnings and thus improve the security and reliability of system greatly. Currently power system security assessment is carried out based on the given contingency list, where the most severe fault scenarios are considered to get the operating mode and corresponding limit. Actually the most severe fault occurs in very rare frequency. That means the power system operating limit will be low to guarantee the security. In the environment of power market, each participant wants to maximize his profit, which conflicts with the principle of the existing security assessment. Moreover the transmission corridors become harder to plan due to environmental concern. This is also the incentive to dig out the transmission capability of the existing lines. How to solve the conflict between the security and the profit of the investment is a problem facing us.

Some pioneers present the concept of risk to do the on-line security assessment [1-10]. The security risk is varied with the topology of the system, corresponding load level [1-2]. However much attention is paid on the historical data based security risk evaluation instead of setting the operating point according to the risk. Our idea is that the security risk of power systems is varied with the operating condition, such as load level, aging status of equipments, environment weather, etc. When the equipments are healthy and environment weather is sunny, the risk might be low. The load level can be deliberately set higher to get more profit. On the contrast, when the transmission lines are ice-coated, the load level can be set lower to make the system secure.

In this paper, the idea of risk based on-line power system security assessment is suggested. Moreover, a precise calculation method of average failure rates of components is put forward, which is the key point of risk. Besides, operating condition based failure rates of components are also analyzed systematically in the paper. Finally, the Monte-Carlo simulation is carried out to demonstrate the viewpoint of the paper.

OVERALL SCHEME OF RISK BASED ON-LINE POWER SYSTEM SECURITY ASSESSMENT

The mathematic model of risk based security assessment is given below.

$$\max_{u}(F)$$

$$F = B_{ic} - P_{ls} \cdot C_{ls}$$

Where, *F* denotes the objective function which should be maximized, *u* represents the operating point, which mainly refer to system topology and load level. B_{ic} is the profit function corresponding to the given operating point. P_{ls} indicates the probability of losing stability, which is the function of system operating point *u* and component failure rate λ_0. While the component failure rate λ_0 depends on the operating condition, such as aging status, environmental weather, operation of relay and recloser, etc. C_{ls} is the loss function of losing stability. The product $P_{ls} \cdot C_{ls}$ is called the security risk index of power system.

In this mathematical model, based on the operating condition, the component failure rate λ_0 can be calculated. Then the operating point *u* can be set to get the maximum profit.

It should be pointed out that the probability of losing stability P_{ls} can be obtained by Monte Carlo simulation once λ_0 and *u* known. In addition, the profit and loss functions (B_{ic} and C_{ls}) are both economical indices which will be discussed in another paper. Therefore, how to calculate component failure rate λ_0 according to the operating condition is the key point the proposed model.

OPERATING CONDITION BASED COMPONMENT FAILURE RATE

A.The Traditional Fault Occurrence Model

Traditionally, the uncertainty of fault occurrence is described using the following model [1]. The probability of fault occurrence on a line can be modeled using the Poisson distribution with a constant fault rate. From the Poisson distribution formula, the probability of no fault in the time period t is given by:

$$P_{no} = \frac{e^{-\lambda_0 t}(\lambda_0 t)^0}{0!} = e^{-\lambda_0 t}$$

where Pno is the probability of no fault occurrence, λo the average fault rate, and t the duration considered. So, the probability of a fault occurring on a line in t is

$$P_O = 1 - e^{-\lambda_0 t}$$

It is noticed that (3) is same as the fault probability following the exponential distribution. In fact, the Poisson and exponential distribution are essentially the same since both are based on the constant rate assumption. If the condition of λot <<1 holds, (3) can be written as:

$$P_O = \lambda_0 t$$

Usually, the average failure rate is approximately replaced by the frequency of fault occurrence, which could be obtained from historical records, since the duration of a fault is always extremely short. The fault occurrence probability is replaced by the forced outage rate (FOR) in some references [10, 12], that is also an approximation. However, we cannot know whether the fault occurs from the practical power system. The only information we can get is whether the circuit breaker open or not, i.e. the recloser works successfully or not. If the recloser closes the circuit breaker successfully, there is no outage. On the constrast, failure of recloser means the corresponding circuit breaker keeps open and there is outage. Aiming at this problem, a method to precisely calculate the average failure rate is presented.

B. The Calculation of Precise Average Failure Rate and Relative Monte Carlo Simulation

Based on the analysis in above subsection, the space diagram can drawn in Fig.1

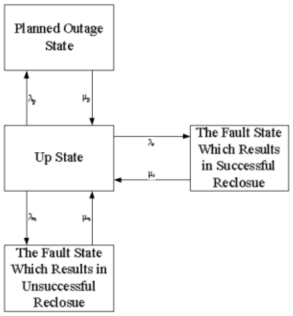

Fig.1 The state space diagram for line fault occurrence

Applying the Markov method to the state space diagram, we can obtain the following results.

$$P_{up} = \frac{\mu_p \mu_u \mu_s}{\mu_p \mu_u \mu_s + \lambda_p \mu_u \mu_s + \lambda_u \mu_p \mu_s + \lambda_s \mu_p \mu_u}$$

$$P_{po} = \frac{\lambda_p \mu_u \mu_s}{\mu_p \mu_u \mu_s + \lambda_p \mu_u \mu_s + \lambda_u \mu_p \mu_s + \lambda_s \mu_p \mu_u}$$

$$P_{ur} = \frac{\lambda_u \mu_p \mu_s}{\mu_p \mu_u \mu_s + \lambda_p \mu_u \mu_s + \lambda_u \mu_p \mu_s + \lambda_s \mu_p \mu_u}$$

$$P_{sr} = \frac{\lambda_s \mu_p \mu_u}{\mu_p \mu_u \mu_s + \lambda_p \mu_u \mu_s + \lambda_u \mu_p \mu_s + \lambda_s \mu_p \mu_u}$$

where Pup, Ppo, Pur Psr are the state Probabilities of the up state, planned outage state, the unsuccessful reclosure state, and the successful reclosure state. λp, λu, λs are the transition rates of the planned outage state, the unsuccessful reclosure state and the successful reclosure state. µp, µu, µs are the recovery rates from the planned outage state, the unsuccessful reclosure state and the successful reclosure state.

It is noticed that the recovery time from the successful reclosure fault state to up state is extremely small, about 1 second. Therefore, µs is extremely large, so (5-8) can be simplified as follows.

$$P_{up} = \frac{\mu_p \mu_u}{\mu_p \mu_u + \lambda_p \mu_u + \lambda_u \mu_p}$$

$$P_{po} = \frac{\lambda_p \mu_u}{\mu_p \mu_u + \lambda_p \mu_u + \lambda_u \mu_p}$$

$$P_{ur} = \frac{\lambda_u \mu_p}{\mu_p \mu_u + \lambda_p \mu_u + \lambda_u \mu_p}$$

$$P_{sr} \approx 0$$

$$f_{up} = P_{up}(\lambda_p + \lambda_u + \lambda_s) = \frac{\mu_p \mu_u (\lambda_p + \lambda_u + \lambda_s)}{\mu_p \mu_u + \lambda_p \mu_u + \lambda_u \mu_p}$$

$$f_{po} = P_{up} \lambda_p = \frac{\lambda_p \mu_p \mu_u}{\mu_p \mu_u + \lambda_p \mu_u + \lambda_u \mu_p}$$

$$f_{ur} = P_{up} \lambda_u = \frac{\lambda_u \mu_p \mu_u}{\mu_p \mu_u + \lambda_p \mu_u + \lambda_u \mu_p}$$

$$f_{sr} = P_{up} \lambda_s = \frac{\lambda_s \mu_p \mu_u}{\mu_p \mu_u + \lambda_p \mu_u + \lambda_u \mu_p}$$

where fup, fpo, fur fsr are the frequencies of the corresponding states(outages/year). In most data collection systems, the outage rates (λp, λu, λs) are not directly colleted. The outage frequencies (fpo, fur fsr) and the repair times (the reciprocals of mean values the repair times are µp, µu, respectively) of components are recorded. Therefore, we have to use to calculate λp, λu, λs. Then it is easy to get the total average fault rate λo=λu+λs. The probability of the faults which result in the unsuccessful reclosure in the total faults is P1=λu/λu+λs, and the probability of the faults which result in the successful reclosure in the total faults is P2=λs/λu+λs. After the total average fault rate λo is obtained, the Monte Carlo simulation method can be applied in sampling the fault occurrence. For a line, a uniformly distributed random number R between [0, 1] is generated. If R＜PO, the fault occurs; otherwise the fault does not occur. This is shown in Fig 2.

Fig.2 Sampling fault occurrence

If the fault occurs on a line, the Monte Carlo simulation method can also be used to sample the fault with a successful or unsuccessful reclosure in a similar way. The fault location, the fault types (single phase to ground, double phase to ground, three-phase, phase-to-phase) and the fault clearing time can also be sampled by Monte Carlo simulation method.

C. The Weather-dependant Failure Rate

The failure rate of an overhead line varies with the weather and other conditions. When the components are exposed to an adverse environment, their failure probabilities increase dramatically. If the historic data (such as the failure frequencies and the repair times) are collected according to the classified weather respectively, the various average failure rate of component in each type of weather can be calculated separately. But now, most data collection systems do not distinguish the weather condition but only respond to an average failure frequency and an average repair time in past years. In terms of the calculation of precise failure rate in above subsection, the weather-dependent failure rate described in reference [1] should be modified as below. If the weather is divided into two basic categories: normal and adverse. Assume that the frequencies of the planned outage are not affected by the weather. We have the failure rates to the planned outage for both normal and adverse weather conditions:

$$\lambda_{ad,p} = \lambda_{no,p} = \lambda_p$$

where, the subscript ad and no denotes the adverse weather and normal weather respectively. λp can be calculated by . Then, the failure rate of unsuccessful reclosure λad,u and the failure rates of successful reclosure λad,s under adverse weather condition can be obtained by solving.

$$f_{ad,ur} = \frac{\lambda_{ad,u}\mu_{ad,p}\mu_{ad,u}}{\mu_{ad,p}\mu_{ad,u} + \lambda_p\mu_{ad,u} + \lambda_{ad,u}\mu_{ad,p}}$$

$$f_{ad,sr} = \frac{\lambda_{ad,s}\mu_{ad,p}\mu_{ad,u}}{\mu_{ad,p}\mu_{ad,u} + \lambda_p\mu_{ad,u} + \lambda_{ad,u}\mu_{ad,p}}$$

The failure rate of unsuccessful reclosure λno,u and failure rate of successful reclosure λno,s under normal weather condition can be obtained by solving

$$f_{no,ur} = \frac{\lambda_{no,u}\mu_{no,p}\mu_{no,u}}{\mu_{no,p}\mu_{no,u} + \lambda_p\mu_{no,u} + \lambda_{no,u}\mu_{no,p}}$$

$$f_{no,sr} = \frac{\lambda_{no,s}\mu_{no,p}\mu_{no,u}}{\mu_{no,p}\mu_{no,u} + \lambda_p\mu_{no,u} + \lambda_{no,u}\mu_{no,p}}$$

Then, the total average failure rate for adverse weather condition is λad,o=λad,u+λad,s, and for normal weather condition is λno,o=λno,u+λno,s.

Therefore, the corresponding failure rates for different kinds of weather condition can be used for on-line power system security assessment. The Monte Carlo simulation method also can be applied for the different failure rates.

Obviously, the method can be extended to the multi-type weather conditions.

In the case of overhead line, it is possible that a line traverses two regions where Region 1 is in the adverse weather and Region 2 in the normal weather. The length exposed to the adverse weather condition is x as shown in Fig 3, therefore the total failure rate of the line

λ_{le} is: $\lambda_{le} = \lambda_{ad} x + \lambda_{no}(1-x)$

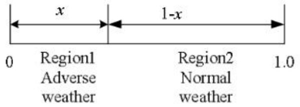

Fig.3 Schematic diagram of line traversing two regions

It is pointed out that the failure rate in region 1 is λad, therefore the fault location probability should be modified as follows. Assumed that the probability of fault location yields the uniform distribution between [0, 1] in normal weather condition. Then the probability of a fault occurring in Region 1 is modified as:

$$P_{l,1} = \frac{x\lambda_{ad}}{x\lambda_{ad} + (1-x)\lambda_{no}}$$

The probability of a fault occurring in Region 2 is modified as:

$$P_{l,2} = \frac{(1-x)\lambda_{no}}{x\lambda_{ad} + (1-x)\lambda_{no}}$$

Obviously, the method can be extended to the cases in which an overhead line traverses more than two regions where different weather conditions are assumed.

D. The Impact of False-Trip of Protection on Failure Rate

The failure operation of protection and its impact on risk assessment has been studied in reference. The paper only focused on the false-trip of protection and its impact. The relays might falsely trip the circuit breakers. Due to the randomicity of relays' false-trips, it is hard to take this factor into consideration. But some kinds of false-trips have rules to be followed and then such kind of false-trips can be considered. We take the false trip caused by "power direction inverse" as an example, which is shown in Fig 4.

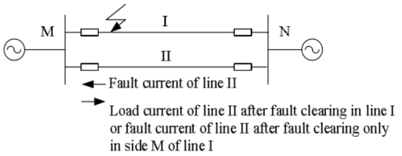

Fig.4 The schematic of false trip of protection caused by "power direction inverse"

In double circuit lines or loop lines which are protected by the pilot protection, when fault occurs on the side M of line I, for line II, the fault power direction of side M is reverse, which sends the blocking signal to both sides to block trip. But after fault clearing in line I, the load power direction of side M in line II is inversed to forward instantly, which stop sending the blocking signal to both sides. At the same time, the load power direction of side N in line II is tuned to reverse instantly, which begin to send the blocking signal to both sides. But for the pilot protection of side M of line II, the blocking signal sent by side M disappeared first, and the blocking signal sent by side N arrives later due to the channel delay shown in Fig 5.

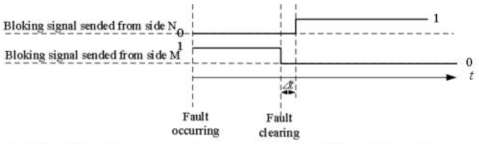

Fig.5 The blocking signal sequences in false-trip of protection caused by "power direction inverse"

Therefore, in the period Δt, the protection of side M of line II are not blocked by any signal and then mal-operates to trip the breaker. Similarly, if the fault clearing time of side M in line I is shorter than that of side N, the "power direction inverse" phenomenon will also appear and cause the false trip of protection. In this case, because the inverse power is the fault power, the phenomenon is more obvious. The false trip of protection caused by the "power direction inverse" in AC systems can be avoided using the time delay coordination. But in AC/DC hybrid systems shown in Fig 6, the false trip of protection caused by the "power direction inverse" due to the failure of phase change in rectifier or inverter and the subsequent DC block is hard to be avoided. If the fault occurs on the line nearby the AC bus of the rectifier or inverter substation, the possibility of phase change failure in rectifier or converter will increase dramatically. The consequence of the phase change failure is DC block.

At the instant that DC is blocked, the fault power direction of side M in line II is inversed to forward, and the relative protection will falsely trip line II as described above. The time from the fault occurring to DC block is too short to be distinguished. The waveforms distortion in one time window caused by phase change failure and DC block will also confuse the direction component. Therefore it is hard to prevent false-trip of relay under this situation. It should be considered in security risk assessment.

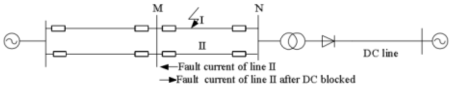

Fig.6 The schematic of false-trip of protection caused by "power direction inverse" in AC/DC hybrid systems

When fault occurs on a line, the false trip of protection of other line generally decreases the connection impedance between the subsystems and generators further, which deteriorates the transient or dynamic performance of power systems. The false trip of busbar protection caused by line fault will yield more serious consequences. Under the condition that no fault occurs on power systems, the false trip of protection will cause a branch open which is a small disturbance and will be corrected by the reclosure.

But for the cases with a fault, the false-trip of another line will worsen the system state and might cause blackout, which has been proven in recent occurred blackouts. Therefore, the false-trip of protection can not be ignored in security risk assessment of power systems. Particularly, the mal-operation should be emphasized when it is incorporated with generator rejection scheme (GRS) and other remedial actions. The probability of mal-operation of protection without faults on power system can be obtained from the historical data of protection management system. The probability of mal-operation of protection with fault in nearby region also can be obtained from the historical data of protection management system.

When fault occurs on double circuit lines, especially nearby the rectifier or inverter, the probability should be larger than that under other situations. Monte Carlo simulation method also can be applied to sample the occurrence of mal-operation of protection once the probabilities of mal-operation are obtained. The mal-operation of protection is treated as an event in the disturbance sequences in time domain simulation of security risk assessment.

II. TEST RESULTS AND ANALYSIS

The relative small WSCC 9-bus test system shown in Fig. 7 is studied to illustrate the idea in this paper.

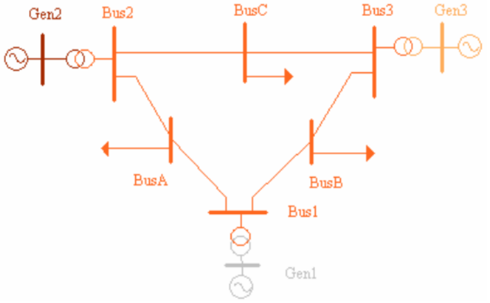

Fig.7 WSCC 9-bus system

Assume that the 40% length of line Bus2-BusC and 50% length of line Bus2-BusA are exposed to the adverse weather condition. The EMC level in substation C is not sufficient and the modification factor is assumed as 2.0, which denotes the probabilities of mal-operation and refuse-operation of protections in substation C is multiplied by 2.0. The probability of mal-operation of protection without faults on power system is assumed as 0.001 for other lines and buses. The probability of mal-operation of protection with fault in nearby region (here, is the neighboring line) is assumed as 0.002. The probabilities of refusal-operation of all kinds of protections are all assumed as 0.01. The three-phase trips do not result in the reclosure. For all lines, fpo, fur fsr are assumed as 1, 0.5, 1 respectively, and μp, μu are assumed as 365, 400 respectively. The probability of fault types is the same as that in reference [1] and the probability of fault location is assumed to yield the uniform distribution. For all buses, the failure rates are assumed as 0.002. For all transformers and generators the failure rates are assumed as 0.004. The fault clearing time is assumed to yield the normal distribution with 0.12s mean and the standard deviation 2%. The time of backup protection is assumed to yield the normal distribution with 0.62s mean and the standard deviation 2%. The time of reclosure is assumed to yield the normal distribution with 1.0s mean and the standard deviation 2%. The insulation aging failures are only considered for transformer Gen3–Bus3, and the survived time past normal life is 1 year.

10000 sample cases are generated using nonsequential Monte Carlo method. The probability of instability Pis is defined as the proportion of the instability cases in the total sample cases. It can be used as the risk index. The time period considered in on-line assessment is 15 minutes and the whole simulation spends about 13 minutes and 30 seconds.

Table 1 The comparison of risk indices in different situation

situation	P_{is}
Basic power flow, the method in this paper is not adopted	0.0011
Basic power flow, the method in this paper is adopted	0.0013
The injection power of Generator 2 increases 40MW, while that of other generator decreases 20MW, and the method in the paper is adopted	0.0021

From Table 1, we can draw some conclusions as follows: compared with the traditional method, the risk index obtained by the new method in the paper is increased because the failure rate is more precise and more information is taken into account. The incremental power of generate 2 also increase the risk index, which will attract the attention of dispatcher.

CONCLUSION

In this paper, the idea of risk based on-line power system security assessment is suggested to achieve the best equilibrium between the security and the profit. The calculation method of precise average failure rates is put forward. Then, the operating condition based failure rates are analyzed systematically. The Monte-Carlo simulation demonstrates the viewpoint of the paper.

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