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Performance of Protection Systems during Catastrophic failures in Power Systems

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Abstract - Catastrophic failures in power systems are rare but not uncommon events. Protection systems play an important role in the progression of events during a catastrophic failure. This paper will examine some of the historical records, and suggest possible improvements to protection systems which can have a positive impact on power system performance during catastrophic failures.

Keywords: Blackouts, Catastrophic Failures, Power Systems, Protection Systems, Relaying

1. Introducton

It is well-known that power systems are subject to load fluctuations, faults, forced outage of equipment, and outages to take care of scheduled maintenance. In some cases, particularly when the power system is in a stressed state, it is possible that a sequence of unanticipated outages, faults, and protection system operations combine to produce a catastrophic failure of the power system leading to major loss of load lasting for a long time. Such events are rare but not uncommon. In many countries de-regulation of the industry has produced load and generation patterns which are quite different from the norm as it existed for several decades prior to de-regulation. Also, incentives for improvements in transmission and substation equipment are often absent in this new environment. Because of the unusual demands on the electric power infrastructure after de-regulation, unexpected patterns of system stress have resulted, and to some extent have led to an increased risk of major blackouts.

Protection systems – relays – are designed to protect power apparatus and systems from damage. This is accomplished by autonomous equipment installed in substations with pre-determined thresholds and logics for taking quick action under contingency conditions. It has been estimated that in a large interconnected power network there may be in excess of 4 million protective devices primed to act when called upon to do so. In general, protective systems are designed to be 'dependable', meaning that if the requisite conditions occur, the protective system MUST act. The action taken is almost always to trip some equipment: line, bus, transformer, generator, etc. A highly dependable system by its nature is less 'secure'. In protection system terminology, less secure implies that the system may act unnecessarily, causing an un-wanted trip. In a healthy power system, there is sufficient generation and transmission capacity to tolerate an occasional un-wanted trip without causing extensive damage However a failure to be 'dependable', i.e. not to trip when a trip is required could be very damaging to the power system. When the power system is in a stressed state, an unwanted trip can lead to serious consequences. It is for this reason that a stressed power system and a mixture of wanted and un-wanted trips by protection systems is often the contributing factors to catastrophic power system failures.

2. Anatomy of a Blackout

Each power system blackout is unique. However, a large majority of blackouts are found to have some un-wanted protection system operations. Perhaps the blackout which illustrates this very well is the blackout which occurred in New York City in 1977. Fig. 1 is a one line diagram of the principal 345 kV transmission lines and major generating stations near Manhattan.

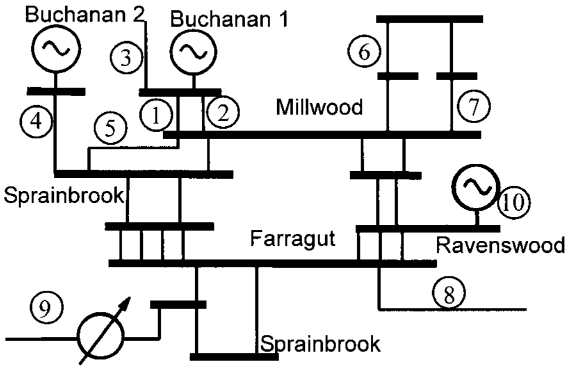

Fig. 1 Transmission network in New York City in 1977 showing major transmission lines, ties, and major generating stations.

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This event occurred on a hot summer day, with high load in the city, and a large amount of power being imported from north, east, and west. During a lightning storm, a fault occurred on line 1, causing a trip of the line. A directional comparison blocking relay on line 2 tripped unnecessarily, causing the power out of Buchanan generator 1 to reverse to north. A breaker failure relay at the station was faulty, and due to the increased flow in line 3 this relay picked up, tripped and went to lock-out, thus removing the generator from the system. The originally faulted lines could not reclose because of a low angle setting on the reclosing relays.

A short time later, another fault occurred on line 4, and line 5 tripped falsely due to a directional comparison blocking relay misoperation. Reclosing was blocked again due to the low angle setting of the reclosing relay. Thus a second generator was also lost to the system. The power shifted to alternative paths from New England, and at this time a defective relay on line 6 picked up due to increased loading, tripping that line. The parallel line 7 was now overloaded beyond its thermal capability, sagged because of the heavy load, and created a permanent fault and was also tripped.

At this time the only ties of the power system of the city were through the east and west connections. The power flow on the line to the East (8) was excessive, and following an operations guide line, the operator tripped this line through supervisory control. The remaining tie to the outside was to the west (9) through the phase shifting transformer, which was severely overloaded, which eventually developed a fault and was also tripped. Now the city was without ties to the rest of the country with a severe load generation imbalance, and a blackout resulted. A loss of field relay (10) at the Big Allis generator also operated tripping the unit making the generation shortfall worse.

There were severe civil disturbances following this blackout, and a number of investigative committees were appointed which led to many design and operational improvements to the power system.

3. Lessons For Protection System Engineers

The events described above and similar events throughout the world point out some important lessons for protection system designers. These lessons have been summarized in literature, but a few key points could be repeated here:

- There are protection system settings which depend upon the state of the power system, and fixed settings may sometimes become inappropriate for the prevailing power system state.
- There are failure modes in protection systems which have been termed “hidden failures” which have the potential of becoming active when power system conditions change during a highly stressed state.
- Under-frequency load shedding may have to be supplemented by supervisory load shedding and under-voltage load shedding.
- As power systems become more complex and as operational considerations in de-regulated environment lead to unusual loading patterns, the use of (SPS) Special Protection Systems also known as (RAS) Remedial Action Schemes may become ever-more important.
- Catastrophic failures of power systems can be made less likely by adopting newer developments in computer relaying and communication networks.

We will describe some of these newer developments in the following sections.

4. Innovations in Protection

Computer relays were developed in 1970s and 1980s. Modern power systems use computer relays extensively. Nevertheless because of the legacy issues, a power system may have substantial number of older electromechanical or electronic relays in service. Where it is not practical to replace all relays with computer relays for economic reasons, it may still be possible to apply computer relays in a supervisory role at critical locations on the power system so that the likelihood of unwanted trips is substantially reduced.

4.1 Adaptive Relaying

Adaptive relaying is a concept which acknowledges that many protective device settings are dependent on power system state. Thus a distance relay back-up zone may depend upon in-feed to the faults. Pick-up settings of overcurrent relays depend upon maximum load levels and minimum fault current levels. Out-of-step relay settings depend upon stability studies which assume certain system configuration and load levels.

In each of these cases, the relay settings should be changed as power system conditions change. In present practice, in order to cover all possible scenarios that the protection system may have to face, the actual protection settings in use are often not optimal for any particular system state. To match the relay settings to the prevailing power system condition, it becomes necessary for the settings to adapt themselves to the real-time power system states as the system conditions change. Adaptive protection allows for automatic adjustment of protection system settings as the power system conditions change. Conceptually, the principle of adaptive relaying can be explained with the help of Fig. 2.

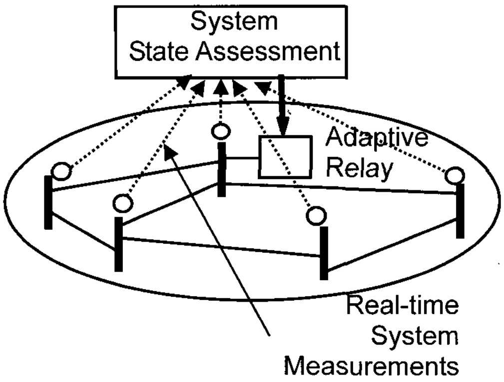

Fig. 2 Adaptive Relaying concept. Real time measurements from the power system are gathered at a central location, and relevant relay settings are adjusted accordingly and communicated to the adaptive relay.

Adaptive relaying is a popular research topic, and considerable literature exists on the subject. We consider a particularly attractive adaptive relaying application, which proposes to change the balance between security and dependability of protection systems. This is illustrated in Fig. 3.

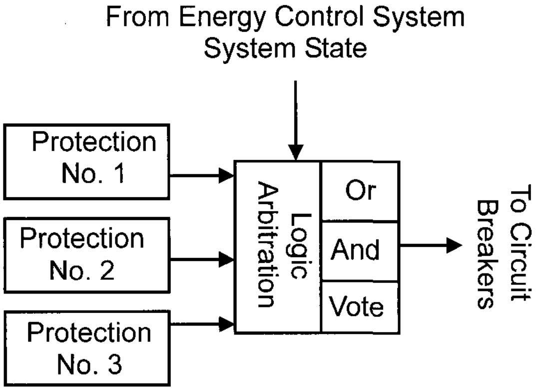

Fig. 3 Adapting the balance between dependability and security of a protection system from a central location.

As mentioned earlier, the normal bias in protection systems is to be "dependable", which makes the system less "secure". Consider the protection system of an important transmission line consisting of three separate protection units: 1, 2, and 3. This system is made highly dependable by logically arranging its outputs in an "OR" logic, so that any protection system can lead to a trip of the line. Of course, if any of the protections mis-operate it will lead to a false line trip. This is the price in "security" paid for designing a highly "dependable" protection. Now assume that at the Energy Control Center a determination is made that the power system is in a highly stressed condition, and it would be undesirable to have a false trip of the line. Thus, one would want the protection system to be "highly secure", and be prepared to pay the price in slightly reduced "dependability". This can be achieved by arranging the output of the three protection systems in a logical "VOTE", meaning that two out of three relays must create a trip signal before the line is tripped. It is clear that in this arrangement there is a reduction in dependability, but the chances of a false-trip are considerably reduced. One could go to the extreme and arrange the logic to be an "AND" function, requiring that all relays must produce a trip signal before the line is allowed to trip. However, this option is too severe for most practical cases, and the middle ground of a "VOTE" function is more suited to system needs.

This adaptive protection concept is well-worth considering for practical implementation at critical facilities on the network. A study of blackouts shows that it is always the false trips which contribute to the cascading of events. Note the false trips of the directional comparison blocking schemes in the event described in Section 2 above. If one could have verified from other protection devices that indeed a trip is justified before the lines were tripped, the events described in Section 2 would have stopped well short of a blackout. There are installations of this type on some power systems, where an arbitration logic unit is added to the protective systems in order to change the security-dependability balance in the trip output logic.

4.2 Hidden Failure Monitoring and Control

Hidden failures in protection systems have been identified as contributing factors to catastrophic failures of power systems. These are failures which by themselves do not cause a relay operation, but when system conditions become stressed, the failure in the relays is such that they produce a false-trip. The breaker-failure relay as well as the overcurrent relay in line 6 in the example of Section 2 is an example of hidden failures of this type.

Given the large number of relays which exist on a power network, it is not possible to assure that there will be no hidden failures anywhere. The exact details of how a hidden failure may occur will depend upon the type of relay in use. One of the papers listed in the bibliography provides a catalog of hidden failures for different types of relays.

Increased maintenance of relays is not always beneficial in this matter. For example, the relay of line 6 in Section 2 had just been maintained a week earlier, and still happened to have a hidden failure in it. In fact, excessive maintenance activity itself may result in hidden failures. It should be noted that computer relays, with their self-checking capability significantly decrease the possibility of hidden failures. Nevertheless, some hidden failures of protection systems are sure to be present in most power systems.

It should be realized that not all hidden failures are equally damaging to the power system. It is possible to study each power system, and determine which protection systems are critical from the point of view of cascading outages if they had a hidden failure. In addition, it is also necessary to determine what event in the power system will lead to a false-trip. This idea has been characterized through a "region of vulnerability". Consider the power system shown in Fig. 4.

Each of the protection systems in the system is assumed to have possible hidden failures. By making simulations of various contingencies, it can be determined which facilities (lines, transformers, buses) are critical to the survival of the power system. Let R be one such relay in the power system. One would now examine what would cause that hidden failure to cause a false trip. For example, if the failure is assumed to be in the carrier receive function of a directional comparison blocking scheme at R, then faults in the shaded region shown in Fig. 4 would lead to a false trip of relay R. Similar analyses are carried out for all types of protection systems.

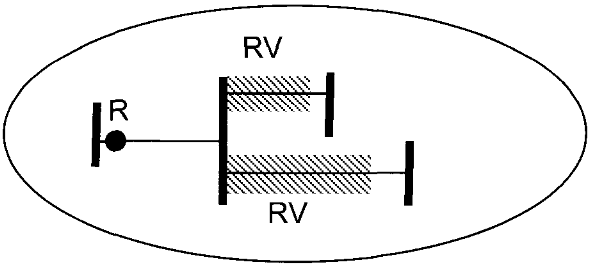

Fig. 4 Regions of Vulnerability. The hidden failure is assumed to exist in relay R. Any fault occurring in the shaded region would cause that particular hidden failure to cause a false trip. The shaded regions are the regions of vulnerability for that hidden failure.

Such an analysis points to those locations in the power system where it is important to assure that no hidden failures in protection systems would cause a false trip. A countermeasure, similar in principle to the adaptive scheme illustrated in Fig. 3 could be deployed at this location. In effect, one would employ a supervisory circuit at the output of the relay, requiring that an independent device confirm that this is a legitimate operation before the trip is issued.

4.3 Remedial Action Schemes

When events taking place on a power system are sufficiently wide-spread so that an effective understanding of the event is not possible with localized information at substations, it becomes necessary to design countermeasures which gather inputs from wider domains of the power system. Such countermeasures, often called Remedial Action Schemes (RAS), or System Protection Schemes (SPS) are becoming more common on modern power systems. At present, most remedial action schemes are based upon pre-computed triggers. An example of a remedial action scheme is shown in Fig. 5.

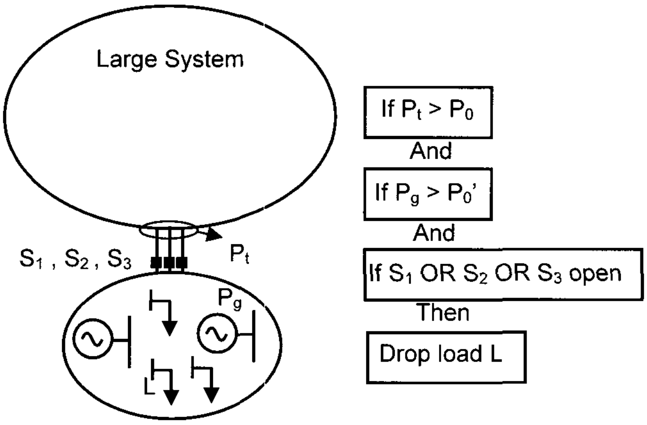

Fig. 5 A generic remedial action scheme designed to protect the system from going unstable by dropping load if certain trigger conditions are met.

This is a generic representation of a remedial action scheme. A large power system is connected to a relatively small system by a few tie lines. Normally the smaller system imports power from the larger system. Under certain conditions of internal load and generation in the smaller system if one of the tie lines is lost the smaller system is sure to go into a blackout because of instability, large load generation imbalance, and fast frequency decay. By planning studies it has been determined that if the load is dropped upon detecting loss of a tie line, and if the internal generation and tie line power flows meet the specified conditions, then a block of load will be dropped. This will save the small system from going out-of-step with the larger system and prevent a catastrophic failure.

Note that the required information for the scheme to operate is gathered from widely separated locations. Use of wide-area measurements for protection is a relatively new concept. It is likely that in the future more and more protection systems of this type will be installed in order to maintain the integrity of the power systems. Although most systems of this type use pre-determined trigger points, it is to be expected that slowly a system which involves real-time data and real-time analysis of events as they occur may make these systems even more effective. This is discussed in the next section.

One of the issues to be addressed is the coordination between multiple remedial action schemes (RAS) operating on the same power system at different locations. It is quite likely that the actions taken by one scheme will affect the trigger points of other schemes. As these schemes proliferate, one should consider a central arbiter for all the remedial action schemes. This is schematically illustrated in Fig. 6.

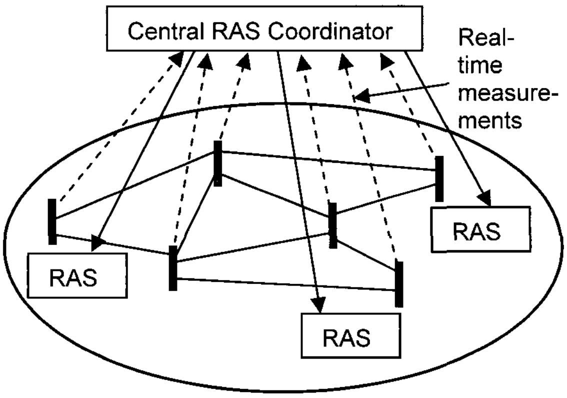

Fig. 6 Central RAS coordinator concept when there are multiple RAS schemes active on a network.

The central RAS coordination task is performed in order to coordinate the actions of the three RAS schemes used in this system. Real time system data is brought to the coordinator, and appropriate coordination software operating on that data determines actions for the RAS systems which would be suitable for the system in its prevailing state.

5. Wide Area Measurements

GPS synchronized real-time measurements taken over wide areas of the power network are becoming ubiquitous. These measurements find their main applications in power system monitoring (State Estimation) and control. However, many protection applications–such as the remedial action schemes described above, tend to verge on being control tasks. No doubt as the wide area measurements become more prevalent, more protection actions using these measurements are likely to be developed.

Wide area measurements by themselves are not of much use. High speed communication facilities to move the measurements over long distances with minimum latency are an essential element of the wide area measurement technology. It is fortuitous that concurrently with the wide area measurement technology, high speed communication using fiber optic channels through ground wires of power lines are also becoming common on most power systems. One could visualize architecture for future development of wide area measurement systems with levels of hierarchy and application tasks at each level as shown in Fig. 7.

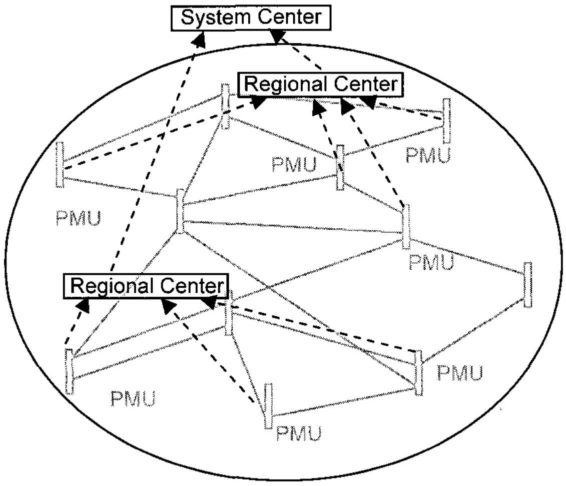

Fig. 7 Hierarchical wide area measurement network for advanced protection, monitoring, and control.

PMUs in Fig. 7 are GPS synchronized phasor measurement units. These units provide real time positive sequence voltage and currents from the substations where they are installed. The data from PMUs is collected at Regional Centers, where the distances to be traveled are shorter, and the amount of data gathered is smaller. The System Center is the place where Energy Management functions are performed. Data from all the regional centers is collected here. It is likely that the distances to be traversed as well as the amount of data to be transferred are greater in this case.

The regional centers may be able to perform the following types of protection related tasks:

(1) Verify regional coordination based on real time system data.
(2) Regional fault location calculations.
(3) Region-wide back-up protection supervision.
(4) Certain adaptive protection tasks which require regional data inputs.

The System Center is able to perform more wide area type protection and control and evaluation tasks:

(1) System-wide state evaluation as to whether the system is in an emergency state.
(2) Adaptive relaying of the type which controls security-dependability balance.
(3) Coordination of multiple remedial action schemes.

(4) System-wide voltage and angular stability assessment, and appropriate protection and control adaptation.

Clearly these ideas are not ready for implementation now, but may be viewed as a road map for the protection and control systems of the future.

6. Summary and Conclusions

Catastrophic failures in power systems are a cause of concern, and protection engineers have much to learn by studying the cascading phenomena and their causes during a major power system disturbance. By judicious use of newer tools such as adaptive relaying, remedial action schemes, and wide area measurements it is possible to improve the performance of protection systems when the power system is under stress. As these newer technologies become prevalent, it should be possible to reduce the incidence of major catastrophic failures of the power systems.

7. Bibliography

In the following, we offer some papers for background reading for the interested reader. This is not a reference list, rather a collection of recent papers where material presented here is more fully developed.

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He is a University Distinguished Professor (Emeritus) at Virginia Tech in Blacksburg, Virginia, USA. His primary research area is the microcomputer based monitoring, protection, and control of power systems. He is a co-author of two books on relaying: *Computer Relaying for Power Systems*, and *Power System Relaying,* and is the editor of and contributor to the book *Handbook of Electrical Engineering Computations*. He is a Fellow of IEEE and was awarded the IEEE Third Millennium Medal in 2000, named the Outstanding Power Engineering Educator by the IEEE in 1991, and received the Power Engineering Educator Award of the EEI in 1986. He received the IEEE Herman Halperin Transmission and Distribution award in 2000. He was the Chairman of the Technical Committee of USNC CIGRE, and Editor-In-Chief of IEEE Transactions on Power Delivery. Dr. Phadke is a Life Fellow of IEEE, and was elected to the US National Academy of Engineering in 1993.