Critical Infrastructures: Protection of the Electrical Power Network

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Abstract. The present chapter discusses the issue of protection of the electrical power systems, addressing all dimensions, from the need of protection to the identified faults and disturbances to the available protection schemes and further considerations, also looking at the challenges brought by recognizing the interdependent nature of the today's electrical power systems.

Keywords: electrical power system, protection, fault, disturbance, interdependencies

1. Introduction

The electrical power systems comprise large and complex machines that are responsible for the generation of electric power in sufficient quantity to meet the present and estimated future demands of the customers, its transmission to the areas where it will be used and then its distribution within those areas. This process is synchronous and continuous.

The protection of the electrical power system is the effort of turning the above process as safe as possible, within an operation environment with effects of disturbances, failures and events that put the system at risk. To ensure the effective protection of the electrical power system, the following three elements (as presented in [3]) are considered fundamental: measurements (data defining the state of the system), data processing, and control.

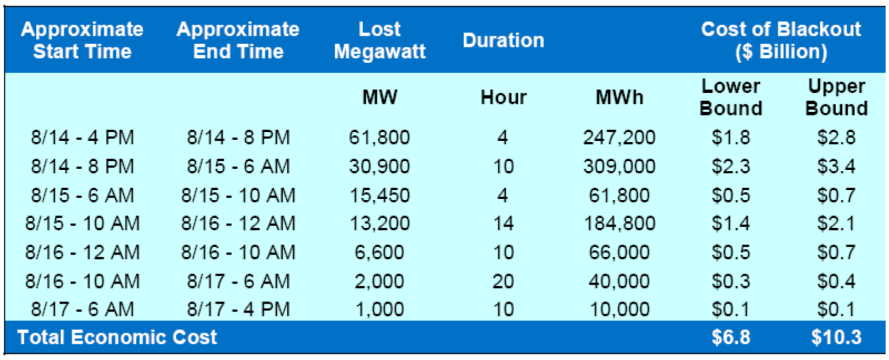
Before going into the details on the protection actions, devices, etc, one needs to summarize what exactly is it protected. A non-exhaustive list of items that need to be protected, as identified in [12] and [6], would include the following: i) human personnel, ii) electrical power system equipment (lines (transmission/distribution), generators, transformers, motors, bus-bars) iii) customer owned equipment, iv) operational integrity of electrical power system (ability to deliver power, stability, power quality) v) customer operations (e.g. large, medium and small industry, financial services, transportation services, telecommunication and other infrastructures' services, etc.).

2. The Need to Protect the Electrical Power System

In general, there are political, economical, social and technological reasons defining the need for protecting the electrical power system.

The electrical power system is a fundamental asset of our modern society and economy, therefore any disruption of its operation has huge negative effects of unforeseen size (unbalances and people reactions, disruption of economic activity, etc.) [7]. However, as mentioned also in [10] and further analyzed in [13], the electrical power systems are subject to disturbances in their normal operation which subsequently cause 'faults', which occur either due to internal technical failures or due to external causes. Therefore, the protection of the electrical power system is necessary so as to ensure: i) Public safety, ii) Equipment protection, and iii) Quality of service, by limiting the extent and duration of service interruption, as well as, minimizing the damage to the involved system components. In any case, as stressed also in [14] safety and prevention of human injury should always take priority over service continuity, equipment damage, or economic losses. It is therefore necessary to prevent or, at least, to detect and clear any fault quickly, since the longer the electrical power system operates in a non-stable condition, the higher the chance that people will be harmed and / or equipment damaged.

On the other hand, the cost required for having electrical power systems perfectly safe or perfectly reliable (by adopting components that do not fail and that require minimum maintenance) would be prohibitive. As stated in [13], risk assessment is performed to define a trade-off for the acceptable levels of risk from disruption in association with relevant costs. That is, the cost of the protection of a system determines the degree of protection that can be incorporated into it. While the cost of protective equipment is a very small part of the electrical power system investment, it must be justified by the value of potential losses from decreased revenue or damaged equipment. Figure 1 provides an overview of the cost of a major blackout that happened in 2003.



Approximate Start Time	Approximate End Time	Lost Megawatt	Duration		Cost of Blackout ($ Billion)	
		MW	Hour	MWh	Lower Bound	Upper Bound
8/14 - 4 PM	8/14 - 8 PM	61,800	4	247,200	$1.8	$2.8
8/14 - 8 PM	8/15 - 6 AM	30,900	10	309,000	$2.3	$3.4
8/15 - 6 AM	8/15 - 10 AM	15,450	4	61,800	$0.5	$0.7
8/15 - 10 AM	8/16 - 12 AM	13,200	14	184,800	$1.4	$2.1
8/16 - 12 AM	8/16 - 10 AM	6,600	10	66,000	$0.5	$0.7
8/16 - 10 AM	8/17 - 6 AM	2,000	20	40,000	$0.3	$0.4
8/17 - 6 AM	8/17 - 4 PM	1,000	10	10,000	$0.1	$0.1
Total Economic Cost					$6.8	$10.3

Figure 1. The economic cost of the Northeastern Blackout, August 2003, USA [11]

3. Types of System Disturbances and Their Effects

It is not feasible to design and build an electrical power system such as to eliminate the possibility of disturbances in service. It is therefore a fact that, infrequently, and at random locations, different types of disturbances will occur, leading to faults incurred on the system. The term ‘disturbance’ means any event, unexpected or foreseen, which requires corrective action to be taken. Sudden disturbances on electrical power systems may result from factors external to the system itself, such as weather or environment, or internal factors such as insulation failure on some component of the system. The following external factors of system disturbances/failures can be identified, as also listed in [8]:

- Weather: one of the main causes of equipment failures; a worldwide survey over several years in the 1980s indicated that about 20% of failures were attributable to weather conditions
- Sudden changes in balance between demand and generation: they can result from numerous causes: loss of transfers from/to external systems, transmission circuit tripping, isolating parts of the system with embedded generation or demand, etc. This type of disturbance is rather frequent, as many other types of disturbances may result in some imbalance during their development.
- Human error: errors of the personnel of a utility may occur at all stages, from planning/design to plant manufacture to plant installation to maintenance/testing to operation. In addition, members of the public may be involved in system errors unintentionally (e.g. kite flying) or consciously (e.g. illegal entry into or attack to parts of the system).

Specifically, the following factors contribute to the risk of severe disturbances: i) Exceptionally severe weather (e.g. causing multiple trippings of transmission circuits), ii) Unexpected and sudden bad weather (causing a rapid increase in demand and increased plant failures), iii) Sudden and large loss of generation, iv) Excessive non-availability of generating plant, v) Failure of anti-disturbance or protection equipment, vi) Errors by control staff, errors by operational staff, errors in planning, errors by field staff, etc.

The disturbances triggered on the system, by the above factors, and that require protective actions can be summarised as [6]:

- Faults and
- Abnormal operation at local and/or system level

3.1 Disturbances Associated with Abnormal Operations

Such types of disturbances include, based on [6] and [8]:

- severe unbalance
- overload
- frequency variations causing plant to behave incorrectly: the acceptable frequency variations are quite small, at the range of 0.005%. According to

the North American standards, any frequency deviations must be corrected within 30 seconds.
- issues with distributed generation: disconnection of substation or generating station, generators going out-of-step or out-of-synchronism with each other.
- under-over-voltage: the voltage tolerances (maximum deviations from nominal voltage) are quite small, as are the allowable times for such deviations to exist
- instability (transient, voltage): inability of a system to remain stable following small signal disturbances about the operating point, as a result of changes in the system and interaction between control mechanisms (e.g. dynamic power oscillation)
- system splitting into smaller parts, due to control actions or failures of equipment

The incidents which could lead to the above conditions (from [8]) are: i) fault on primary equipment, ii) equipment maloperation, iii) communications maloperation, iv) equipment ratings exceeded, v) steady state and transient limits exceeded. In addition, some of these disturbances are predictable (in the sense that the lead times of the event will often give time for preventive action to be taken) with warning times of hours, days, or even months. For example, in the event of loss of generation or import from neighbor system, the lead time is 5 sec to 1 min, depending on corrective actions available, and minutes to hours if no warm-standby plant available. In the event of reduced generation, minutes to hours if the reduction is caused by shortage of generating plant and up to days if this results from fuel shortage.

3.2 Classification of Faults

According to [4] faults are primarily classified into ‘active’ and ‘passive’. The ‘active’ fault is when actual current flows from one phase conductor to another (phase-to-phase), or from one phase conductor to the earth (phase-to-earth). This type of fault is further classified into ‘solid’ and ‘incipient’. The solid fault occurs as a result of an immediate complete breakdown of insulation (e.g. a cable was dug up during works). This type of fault must be cleared as quickly as possible, otherwise there will be increased and multi-types damage at fault location and danger to operating personnel. The ‘incipient’ fault, on the other hand, is a small fault that starts but triggers cascade and catastrophic failures (e.g. a burning of insulation may spread further to adjacent insulations and turn to a ‘solid’ fault).

The passive faults are in fact the conditions that are stressing the system beyond its design capacity, thus leading to active faults.

There are also other classifications of faults (for further details the reader is referred to [4]), like:

- Transient Vs permanent**:** transient faults are faults, which do not damage the insulation permanently and allow the circuit to be safely re-energized after a short period. They occur mainly on outdoor equipment where air is the main insulating medium. Permanent faults comprise permanent damage to the insulation. In this case, the equipment has to be repaired and not recharged before repair/restoration.

- Symmetrical Vs asymmetrical: a symmetrical fault is a balanced fault with equal sinusoidal waves about their axes, and represents a steady-state condition. An asymmetrical fault presents a DC offset, which is transient and leads to the steady state of the symmetrical fault after a period of time.

4. Protection Measures to Minimize the Impact of Disturbances

The significant factors which affect the impact of disturbances have been discussed in section 3. This section discusses the measures (including the automatic mechanisms and “defense plans”) that should be taken in the management, planning and operation phases of electrical power systems to minimize the effects of disturbances. Many more details are provided in [9] for those interested. Protection measures often contain three main elements: detect a possible disturbance and its type, assess the best way to prevent it or minimize its effect at the extent possible, and restore normal operation. In general, measures are taken with the help of hardware and/or software components, however, human involvement in decision making and implementation of protection processes are equally important. The human involvement in decision making is even more important during the operational phase, particularly during the development of a disturbance. Therefore, it is appropriate to consider also the level of training of system operators.

4.1 Measures in the Planning, Operational, and Restoration Timescale

The system engineers are the ones defining the protection plans, as well as, what specific protective and control measures will be needed during system operation. Some of the measures (for instance, under-frequency load shedding), are addressed in the planning phase, while others (e.g. inter-tripping schemes with local impact, the necessity of which emerges at short notice) are addressed directly in the operational plan.

In the event of a system disturbance, the following actions are taken, based on the operational memoranda and procedures and any special protection schemes or coordinated defense plans employed by the plant engineers: i) open breaker and under frequency relays (isolated fault), ii) switch capacitors, iii) load shedding/disconnection, iv) divide system into islands, v) do not respond, vi) alarm signal, vii) generation margins adjustment, viii) demand adjustment

Specifically for the event of high frequency experience, the system operators act following a very precise action plan. This plan considers that any demand/load disconnection will be avoided at the extent possible. Instead, they will implement measures to increase the frequency of the generation. This way, the reduction of demand happens in full control, by first exploiting voltage reductions across the system and then load reductions. The process is called load management. The system owners sign agreements with the larger consumers to disconnect agreed amounts of demand. For domestic consumers, disconnection is performed selectively on water and space storage heating systems. Contracts with neighboring systems are also taken into account, which allow adjustment of power transfers to bring the system into stability.

Concerning the restoration phase, there is a need for a combination of operator decisions and automatic control actions. The objective of the restoration phase is to bring the system back to equilibrium, that is, as much demand as possible is being supplied at normal frequency, voltage and security levels. In the case of losing a big part of the generation, the recovery of the system would be very difficult. However, the disturbances are often relatively localized, such that the remaining system provides a stable source of frequency and power for starting-up the disturbed area as soon as the required repairs are completed. A key to the restoration phase is also the extent to which the disturbance was foreseen, ranging from no warning at all with a sudden event, to hours or days with fuel shortages. The operator will act following a review of the conditions and based on the strategic decisions to be made. The possibility of further faults must be also considered during the restoration phase.

4.2 Measures in the Communication Facilities (SCADA)

Electrical power systems need very secure (physical rather than content) communication links for data and speech. Such links are either system-wide or local, between substations. The way to improve the security of communications is by avoiding as much as possible the dependence on any one provider. Usually, the system poses its own communication channels for connecting its equipment (e.g. power line carrier) or channels are hired from external providers such as public communications networks or even other industries with widespread communication networks, such as railways. It is also a common practice in electrical power systems to duplicate (at least) the SCADA (Supervisory Control and Data Acquisition) and EMS (Energy Management System) systems within one Control Centre building. In some cases, the utilities go further than this and provide backup of whole Control Centers.

5. Protection Techniques and Devices

As stated in [3] a protection system has three main functions: i) safeguard the entire system to maintain continuity of supply, ii) minimize damage and repair costs where faults happen, iii) ensure safety of personnel.

These requirements are necessary, firstly for early detection and isolation of faults, and secondly for prompt action and removal of faulty equipment from the system. In order to carry out the above functions, the protection system must have the following qualities (clearly identified in [3] and [13]):

- Selectivity: accurately identify a problem and only react if there is a problem

- Stability: leave all healthy parts of the system intact to ensure continuity of supply
- Sensitivity: ability to detect even small disturbed conditions and act before the fault causes irreparable damage
- Speed: react quickly, thereby minimizing damage to the surroundings and ensuring safety to personnel
- Reliability: operate long time without acting and then act properly
- Security: not operate when not supposed to

The job of protection is a function of many elements. In the following, a brief outline of various components that are utilized in protecting an electrical power system is provided. The main source of the information is [5]. The items below are extensively used in any protective system and their design requires careful study and selection for proper operation.

- Current and voltage transformers to step down the high voltages and currents of the electrical power system to convenient levels for the relays to deal with
- Protective relays to sense the fault and initiate a trip, or disconnection
- Circuit breakers to open/close the system based on relay commands
- Batteries to provide power in case of power disconnection in the system
- Communication channels to allow analysis of current and voltage at remote terminals of a line and to allow remote control of equipment.

5.1 Protection System Components

Based on [6], [5] the following components are distinguished:

- Fuses: the most common and widely used protective device in electrical circuits. Fuses are independent, self-destructing components, aiming to save the equipment on the other part of the system.
- Instrument transformers: monitor and give accurate feedback about the operation status of a system. They continuously measure the voltage and current of the electrical power system and are responsible to give feedback signals to the relays to enable them to detect abnormal conditions.
- Circuit breakers: break the circuit carrying fault currents for a few cycles based on feedback/instructions from the relays. They are basically switches to interrupt the flow of current and they open on relay command. They are used in combination with relays, to detect and isolate faults, where fuses are unsuitable. The important characteristics of circuit breakers from a protection point of view are the speed of reaction (the main current is opened after the respective impulse is received) and the capacity of the circuit that the main contacts are capable of interrupting.
- Tripping batteries: they give uninterrupted power source to the relays and breakers that is independent of the main power source being protected. They have an important role in protection circuits, as without them relays and breakers will not operate, making the performance of the whole network unacceptable.

- Relays: they convert the signals from the monitoring devices/instrument transformers (mostly voltages and currents) and give instructions to open a circuit under faulty conditions or to give alarms when the equipment being protected is approaching its capacity limits. This action ensures that the remaining system remains untouched and protects it from further damage.

With the advancement in digital technology and use of microprocessors, the relays became able to monitor various parameters, which give complete history of a system during both pre-fault and post-fault conditions. This led to the name of Intelligent Electronic Devices (IEDs), which is considered the component of the future protection of electrical power systems.

5.2 Intelligent Electronic Devices

Intelligent Electronic Devices (IED) according to [5] comprise the second generation of microprocessor relays that are, in addition, utilized as data acquisition units and for the remote control of the primary switchgear. This utilization of the relays has been inspired by the fact that faults do not happen so often and in all parts of a system, therefore, relays can serve other duties as well, apart from their main protection function. In addition, utilizing the protection relays also for data acquisition and control, it achieves integration and better interoperability of the various systems such as protection, supervisory control and data acquisition.

Furthermore, the use of optical fibers in digital communications allowed the exchange of information between the relay and the substation control level to be much more reliable. The following information is typically available from the relay: i) measurement data of current and voltage, ii) information stored by the relay after a fault situation, iii) relay setting values, iv) status information on the circuit breakers and isolators, v) event information.

The communication link to the relay can also be used for control purposes, i.e. i) circuit breaker open/close commands, ii) remote reset of the relay or auto-reclose module, iii) changes to the protective relay settings.

The functions of a typical IED can be classified into protection, control, monitoring, metering and communications. Specifically, the communication capability of an IED is one of the most important aspects of modern power and protection systems. The communication can be power line carrier, microwave, leased phone lines, dedicated fiber, and even combination of these. There is a strong need to have adequate back-up in case communication is lost, e.g. as a result of a disturbance.

An efficient combination of IEDs, programmable logic controllers (PLCs) and computers to monitor and communicate could lead to a good level of electrical power system substation automation in order to improve customer service. A computer is actually the most useful addition to record all the information about the various parts of the electrical power system. Adding computers at the substation level, further allows the build-in intelligence to be moved to the substation level. That intelligence reduces the amount of data that must be communicated between substations and the main station. For example, information can be retrieved as and when needed from databases maintained at the substation.

5.3 Failures of Protection Equipment and Need for Maintenance

Protection systems do fail. As stated in [13], there are four primary causes of such failures: instrumentation distortion, control failures, relay equipment failures, and incorrect relay settings. Instrumentation distortion is usually caused by saturation from excessive inputs. Failures of breakers or other faults can cause control failures. The reliability of relay equipment depends on the adopted design and manufacturing processes, as well as, their proper settings. Hence, the designers of protection systems must know which relay is best suited for a particular application and how to set the relay parameters to obtain the proper selectivity and sensitivity. The overall reliability of the protection system is increased by implementing overlapping zones of protection, as well as, adding redundancy and backup in the protection equipment.

6. The Electrical Power System as an Inter-dependent Infrastructure

Today's electrical power systems consist of several and heterogeneous components [1], [2], all connected through complex electrical networks/grids. The trend in recent years is that private and public electrical power systems (utilities) operate in interconnected power grids, thus increasing the reliability of the whole system but also generating marketing opportunities. This interconnection evidently improves the reliability of each member utility because any loss of generation can be transparently covered by the neighbour utilities. On the other hand, this interconnection increases the complexity of the electrical power system. Then, the concepts of protection, security and reliability of service become much more significant, for both individual utilities and the interconnected electrical power system. Even much more importantly, when studying such complex systems, one must consider also the interdependencies among the involved plants, as well as, the interdependencies between the electrical power system and other critical infrastructures.

Nowadays, public health, economy, security and quality of life heavily depend on the resiliency of a number of critical infrastructures, including energy, telecommunications, transportation, emergency services and many others. The technological advances and the necessity for improved efficiency resulted in increasingly automated and interlinked infrastructures, with consequences on increased vulnerabilities to accidental and human-made disturbances. What may appear as different parts of our societies, does indeed depend on and influence each other. E.g. an apparently irrelevant event like a small social conflict, a thrown cigarette or a delayed disposal of waste can, under similar conditions, either vanish without any significant impact or trigger riots, forest fires or epidemics. In a very real sense, infrastructures and the environment are interdependent.

There are four different types of interdependencies of critical infrastructure systems:

- **Physical interdependency**: arises from a physical linkage between the inputs and outputs of two components. E.g. an output of one infrastructure is required as input to another infrastructure for it to operate

- **Cyber interdependency:** the state of an infrastructure depends on information transmitted through the information infrastructure (computerization and automation of modern infrastructures and widespread use of supervisory control and data acquisition (SCADA) systems)
- **Geographical interdependency**: a local environmental event can create state changes in all involved infrastructures; implies close spatial proximity of the components of different infrastructures.
- **Logical interdependency:** the state of each infrastructure depends on the state of the other via a mechanism that is not a physical, cyber, or geographic connection. For example, various policy, legal, or regulatory regimes can give rise to logical linkage among two or more infrastructures

Modeling the interdependencies among such interlinked infrastructures and assessing interdependencies impacts on the ability of the system to provide resilient and secure services are of high importance. Following such interdependency analysis, steps can be taken to mitigate the identified vulnerabilities. Critical infrastructure protection is therefore a priority for most of the countries, and several initiatives are in place to identify open issues and research viable solutions in this highly challenging area, especially to identify vulnerabilities and devise survivability enhancements on critical areas.

7. Conclusions

Evidently, the operation of the Electrical Power System affects our everyday life, across many dimensions, from economical to societal to political. Therefore, Electric Utilities allocate a justifiable part of their budget to installing, operating and maintaining the extra layer called “Protection System”. As shown, the protection system undergoes significant evolutionary changes through the years; the protection devices utilize the technological advances, the algorithms that allow for the orchestration of the protection devices become more intelligent and the protection processes become more and more automated, utilizing the telecommunication infrastructure. At the same time, the complexity of the resulting system drastically increases due to the increase in the impact of the Electrical Power System to other critical infrastructures in our society, as well as, due to the increase of the impact of other infrastructures to the operation of the Electrical Power System. The challenge for the academia and industry is to join forces and make sure they find the necessary balance, to keep the operation of the system relia ble and with high quality of service.

8. References

1. Chiaradonna S., Di Giandomenico F., Lollini P., “Interdependency Analysis in Electric Electrical power systems”, in *Lecture Notes in Computer Science*, Springer Berlin / Heidelberg

2. CRUTIAL: European Project CRUTIAL - critical utility infrastructural resilience (contract n. 027513). Available: http://crutial.cesiricerca.it

3. Hewitson L.G., Brown M., Balakrishnan R, "Need for protection", in *Practical Electrical power systems Protection*, Burlington, MA: Elsevier, 2004.

4. Hewitson L.G., Brown M., Balakrishnan R., "Faults, types and effects", in Practical Electrical power systems Protection, Burlington, MA: Elsevier, 2004.

5. Hewitson L.G., Brown M., Balakrishnan R., throughout the chapters of Practical Electrical power systems Protection, Burlington, MA: Elsevier, 2004.

6. Johnson Brian K.. "Electrical power system Protection and Relaying" in lectures of ECE525-Electrical power system Protection and Relaying at the Department of Electrical and Computer Engineering, University of Idaho, Moscow, 2010

7. Knight U.G., "Disturbances in Electrical power systems and Their Effects", in *Electrical power systems in Emergencies - From Contingency Planning to Crisis Management*, John Wiley & Sons, 2001

8. Knight U.G., "Disturbances in Electrical power systems and Their Effects" and "The Natural Environment-Some Disturbances Reviewed", in Electrical power systems in Emergencies - From Contingency Planning to Crisis Management, John Wiley & Sons, 2001

9. Knight U.G., "Measures to Minimize the Impact of Disturbances" and "Plant Characteristics and Control Facilities for Emergency Control, and Benefits to be Obtained", in Electrical power systems in Emergencies - From Contingency Planning to Crisis Management, John Wiley & Sons, 2001

10. McLean Ian, "Certificate in Electrical power system Protection" IDC Technologies, USA, Rep. on training courses, 2010.

11. Saha Bansari, "The Economic Cost of the Blackout-An issue paper on the Northeastern Blackout, August 14, 2003", ICF Consulting, Fairfax, VA

12. Soman S.A.. "Electrical power system Protection" in *lectures of Electrical power system Protection at the Department of Electrical Engineering, IIT Bombay.*

13. Wall Richard W., "Introduction to Practical Electrical power system Protection", in *lectures of EE526: Protection of Electrical power systems II, Department of Electrical Engineering, University of Idaho*, Moscow, 2005. Available: http://www.ece.uidaho.edu/ee/classes/ECE526S05/text/Ch1.PDF

14. Wikiversity. Power Protection-Intro. Available: http://en.wikiversity.org/wiki/ Power_Protection-Intro

15. Zima M., *Special Protection Schemes in Electric Electrical power systems*, Swiss Federal Institute of Technology, Literature survey, 2002