ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DEPENDENT FAILURES AND FAILURE PROPAGATION IN ELECTRIC POWER SYSTEMS

M.Sc. THESIS

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Department of Electrical Engineering

Electrical Engineering Programme

Thesis Advisor: Prof. Dr. Aydoğan ÖZDEMİR

JUNE 2013

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Keysan-SAEILAILONAHAR, a **M.Sc.** student of ITU **Graduate School of Science Engineering and Technology** student ID 504101024, successfully defended the **thesis** entitled "**DEPENDENT FAILURES AND FAILURE PROPOGATION IN ELECTRIC POWER SYSTEMS**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my parents and fiance,

FOREWORD

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ABBREVIATIONS

CAI	**:** Commonwealth Associate Inc.
CAT	**:** Cascade Analysis Tool
HF	**:** Hidden Failure
NERC	**:** North American Electric Reliability Council
PCG	**:** Protection and Control Group
RTE	**:** French transmission system operator
TRELSS	**:** Transmission Reliability Evaluation of Large Scale Systems

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DEPENDENT FAILURES AND FAILURE PROPAGATION IN ELECTRIC POWER SYSTEMS

SUMMARY

Reliability is defined as the ability of a device or a system to perform its intended function over a specified time period under specified environmental operating conditions.

An outage event involving two or more components, or two or more units based on IEEE standards is named as multiple outage event. In the same way a multiple outage event in which one outage occurrence is the consequence of another outage occurrence, or in which multiple outage occurrences were initiated by a single incident, or both is named related multiple outage event. Each outage occurrence in a related multiple outage event is classified as either a primary outage or a secondary outage depending on the relationship between that outage occurrence and its initiating incident. Primary outage is an outage occurrence within a related multiple outage event which occurs as a direct consequence of the initiating incident and is not dependent on any other outage occurrence. Secondary outage is an outage occurrence which is the result of another outage occurrence.

Cascading failures are processes in which initial outages of electrical power system can propogate to more outages and cause large blackouts.

This study presents cascading outage propagation phenomena for the Thrace part of Turkish National Power Transmission System. This part includes more than 120 154 kV and 380 kV power transmission lines/cables and more than 100 transformers (power transformers and autotransformers). We used 7-year transmission line outages data of the region collected during 2000-2006 period. The average value of propagation of the line outages is calculated from the network data. The distribution of the total number of line outages is predicted from the propagation and the initial outages using a Galton–Watson branching process model of cascading failures.

ELEKTRİK SİSTEMLERİNDE BAĞIMLI HATA VE ARIZA YAYILMASI

ÖZET

Enerji, ekonomik ve sosyal kalkınma için önemli bir kriterdir. Özellikle 1970 yılından bu yana, tüm dünyada daha fazla önem kazanmıştır. Buna göre, enerji yönetimi ve planlama özellikle kuralsız enerji piyasaları var olan ve gelişmekte olan ülkelerde daha önemli hale gelmiştir.

Elektrik enerjisi tedarikçilerinin temel amacı; tüketicilere güvenilir ve tabii ki de ekonomik enerji sağlamaktır. Güvenilirlik; genel anlamda özel çevre ve çalışma koşulları altında, belirli bir süre içerisinde bir cihazın ya da bir sistemin amaçlanan işlevlerini gerçekleştirmek için yeteneği olarak tanımlanır. Bu tanım, ayrıca şu şekilde ifade edilebilir; güvenilirlik bir parça veya sistemin amaçlanan çalışma koşulları altında, amaçlanan gelecek dönem için işlevini doğru bir şekilde yerine getirebilmenin olasılığıdır. Güç sistemi tasarımında önemli faktörlerden biri de ekonomik faktördür. Bu yüzden açıktır ki, bu ekonomik ve güvenilirlik kısıtlamalar rekabet edebilirler.

Bileşen veya birimlerin iki farklı durumları vardır. Bunlar “in service” yada “kesinti durumu” olarak tanımlanır. Bileşen veya ünite enerjilendirildiğinde veya tam sisteme bağlandığında, “in service” durumu olarak adlandırılır. Diğer taraftan, bileşen veya birim kısmen veya tamamen izole olduğunda ve “in service” durumunda değil ise, hata durumu diye adlandırılır.

Kesinti tanımları ve endeksleri; sistem planlama modelleri, işletme ve bakım planlama ve de sistem tasarımına yönelik olarak kullanılmaktadır. Güvenilirlik hesaplamaları için gerekli olan iki bileşen verilerinin temel tipi, sistem kesintisi oranları ve kesinti süreleri ve kaç defa anahtarlama yapıldığıdır. Ağ güvenilirliği tahmin etmek için kullanılan tüm yöntemlerin temel amacı, bu kesinti oranları ve

kesinti süreleri gibi bileşen parametreleri kullanarak sistem güvenilirliğini hesaplamakdır.

IEEE standartlarına göre, iki veya daha fazla bileşen, ya da iki veya daha fazla birim içeren bir kesinti durumunda, “çoklu kesinti olayı” olarak adlandırılır.

Aynı şekilde bir çoklu kesinti durumunda, bir kesinti başka bir kesinti oluşumu sonucu meydana geldiğinde ya da birden çok kesinti oluşumları, tek bir olay tarafından başlatılan ya da her iki durumda “related multiple outage” olarak adlandırılır. “Related multiple outage” durumunda her kesinti meydana birincil kesinti veya ikincil bir kesintisi olarak, kesinti oluşumu ve başlatan olay arasındaki ilişkiye bağlı olarak sınıflandırılmaktadır. Bir “related multiple outage” olayı içinde birincil kesintisi, kesintiyi başlatan olayın doğrudan bir sonucu olarak ortaya çıkar ve meydana gelen diğer kesintilere bağımlı değildir. İkincil kesinti ise başka bir kesintinin meydana gelmesinin sonucu ortaya çıkan bir kesinti olayıdır.

Arıza yayılması, elektrik iletim şebekesinde ilk hatanın daha yaygın kesintilere yayılmasından ve büyük elektrik kesintilerine neden olabilecek bir süreçtir. Büyük ölçeklı enerji ağlarında cascading hatası nadir bir olay olsa bile yine de toplum ve ulusal güvenlik için bir risk sayılır. “Cascading hataları” normalde “single line” kesintileri gibi bireysel hataların kombinasyonundan meydana geldiği için ve bu kombinasyonlarla ilgili tahmin yürütmenin zor olduğu görüldüğü için günümüzdeki araştırmaların önemli miktarı, bileşik şartların bir şebekeyi nasıl kararsız bir duruma yöneltebildiği sürecini takip etmektedir.

Son araştırmalar, koruma sisteminin sadece olası ilk olaylarda değil hataların yayınlanmasında da önemli bir rol oynadığını göstermektedir. Empedans koruma röleleri, yüksek gerilim iletim hatlarında en çok kullanılan koruyucu cihazlardır. Ne yazık ki; “cascading arızaları” süresinde gereksiz yere “over trip” yapabilirler. Bir başlangıç olayı veya olaylarının reaksiyon serisinin kesin modellemeye ihtiyacı olduğu için, “cascading kesintisinin” risk değerlendirmesi son derece karmaşıktır.

Bu çalışmada kullandığımız yöntem dallanma sürecidir. Dallanma sürecinden daha iyi bir kavram elde etmek için, aynı tür nesnelerin yeni nesiller oluşturabildiğini varsayalım; bu nesneler insan, bakteri ve benzeri gibi olabilirler. Tanımlanan nesnelerin başlangıç seti, "sıfırıncı nesil" olarak adlandırıldığında ve bu nesil çocuk sahibi olduğunda "birinci nesil" elde edilir. Birinci nesilin çocukları ise ikinci nesil olarak adlandırılmakta ve bu şekilde devam etmektedir. Unutmayalım ki; bu süreç doğrudan şans olaylarından etkilenmektedir. Her nesil bağımsız ve rasgele sayıda yeni nesiller doğurmaktadır. Dallanma süreçleri, çeşitli uygulamaların "cascading" modellemesinde kullanılmakta fakat "cascading arıza riski uygulaması" için yeni bir yöntem sayılmaktadır.

Bu çalışma, Türkiye Elektrik İletim A.Ş (TEİAŞ), Trakya bölgesi için "cascading" arızalarının yayılma süreçlerini sunmaktadır. Bu bölge 120'den fazla 154 KV ve 380 KV enerji nakil hatları ve kabloları ve de 100'den fazla transformatörler (güç transformatörleri ve ototransformatörler) içermektedir. TEİAŞ datalarına göre, Trakya bölgesi Türkiye`nin en çok enerji tüketen bölgesidir. TEİAŞ'ın geçmiş kayıtlarına göre Trakya bölgesindeki kesintilerin sayısı, sistemin diğer bölgelerinden ve aynı zamanda beklentilerinden çok üstündedir.

Biz bu çalışmada; 2000-2006 döneminde toplanan bölgenin 7 yıllık iletim hattı kesintilerinin verilerini kullandık. Hat kesintisi yayılımının ortalama değerini ise ağ verilerinden hesapladık. Hat kesintilerinin toplam sayısının dağılımı; yayılma, ilk kesintiler ve "cascading hataları modeli" için kullanılan "Galton-Watson" dallanma süreci kullanılarak tahmin edilmektedir.

1. INTRODUCTION

Technology plays an important role in daily life nowadays. It evolves rapidly and the resulting products become irreplaceable in our daily lives. One of the main inputs of the technology without any doubt is the energy, which is generated by a wide variety of recources.

Energy, which is the criterion for economical and social development, has gained more importance all around the world, especially since the 1970's. Accordingly, energy management and planning has become more essential in developing countries, especially in the ones who have deregulated energy markets.

The main goal of the electrical energy suppliers is to provide reliable and of course economical energy to the consumers. Reliability is defined as the ability of a system to perform its intended function over a specified time period and specified environmental conditions [1]. The need for probabilistic evaluation of system behavior has been recognized since at the 1930s [1]. Words like "reliability" and "effectiveness" first used in the 1938 paper by Deam [2].

One of the vital factors in power system design is economical factor. It is evident therefore that the economic and reliability constraints can be competitive [3].

Valid and helpful knowledge are costly to gather, however it ought to be recognized within the long-term that it will be even costly not to collect them [1,4]. The outage definitions and indices are intended to use in system planning models, operations and maintenance planning, and system design [6]. Two basic types of component data are required for the calculation of system reliability; namely, outage rates and outage durations or switching times [7]. The main goal of all methods used to estimate the network reliability is to calculate system reliability using component parameteres such as outage rates and outage durations [7].

It is clear that a single circuit fault (outage) occurrence should result no loss of supply from the transmission system [8]. Cascading failure is a process in which initial failure in electric power transmission network may propagate to more widespread outages and cause large blackouts. In a real power system, a significant amount of load shedding caused by dynamic instabilities and voltage collapse due to lack of reactive power are the main reasons leading to cascading tripping of a series of system components [9]. Cascading failures caused difficult to predict combination of individual events, such as single line outages [10]. Since cascading failures are normally caused by combination of individual events like single line outages and as it is difficult to predict these combinations, recently, considerable amount of researches has tackled the problem of identifying compound contingencies that could place a grid in an unstable condition [10].

Recent researches shows that the power protection system plays a major role not only in any possible initial events, but in further propagation of failures [11]. Impedance protective relays are the most widely used protective devices in high voltage transmission lines. Unfortunately, they may unnecessarily over trip while cascading failure occures [12]. The risk assessment of cascading outage is extremly complicated as it needs exact modeling of a reaction series to an initiating event or events [13].

To have a better concept of branching process, let’s imagine objects that can generate new objects of the same kind; these objects can be men or bacteria reproducing by familiar biological methods, or neutrons in a chain reaction. An initial set of the described objects which we name to be 0-th generation, have children which are named to be the first generation; their children are the second generation, and so on. Do not forget that the process is directly affected by chance events [14]. Branching processes have been used in several applications to model the cascading processes, but their application to the risk of cascading failure is new [15-17].

This study presents cascading outage propagation phenomena for the Thrace part of Turkish National Power Transmission System. We used 7-year transmission line outage data of the region collected during 2000-2006 period [19]. The average value of propagation of the line outages is calculated from the outage and network data. The distribution of the total number of line outages is predicted from the propagation and the initial outages using a Galton-Watson branching process model of cascading failures.

In chapter 2 we will review the reliability, reliability indices and system reliability calculations. In chapter 3, we will give a brief description of cascading failures. In chapter 4, we will overview the branching processes and Borel-Tanner distribution function. Finally in chapter 5, we will show the analysis for the sample system and in chapter 6 we will terminate the study with the conclusions derived from the study.

2. RELIABILITY

2.1 Reliability History

Electric power systems are expected to supply the electrical energy needs of the customers as economic as possible and as reliable as possible regardless of the size of the customer [1]. Reliability is defined as the ability of a system to perform its intended function over a specified time period and specified environmental conditions. The definition can also be stated as: reliability is the probability of a component or a system performing its function adequately, for the future period of time intended, under the operating conditions intended.

The need for probabilistic evaluation of system behavior has been recognized at 1930s. It could be questioned that why these methods have not been used before this date. The main reasons were lack of data, limitations of computational resources, lack of realistic techniques, aversion to use the probabilistic techniques and a misunderstanding of the significance and the meaning of probabilistic criteria and indices. None of these reasons are valid nowadays as most utilities have their related database for reliability analysis, computing facilities are greatly enhanced, evaluation techniques are highly developed and most of the engineers are aware of the importance of probabilistic techniques. Consequently, there is no need to artificially constrain the inherent probabilistic nature of a power system into a deterministic framework. The common concept behind all probabilistic techniques developed in power system engineering and of course in reliability engineering is to recognise that all input, output and also events in the system are probabilistic variables [1].

Observe the use of such words as “reliability” and “effectiveness” in the 1938 paper by Deam:

“One of the difficult problems faced by those responsible for planning of electric supply systems is that of deciding how far they are justified in increasing the investment on their properties to improve service reliability. While this problem is not at all new in the industry, it has nevertheless taken on greatly increased significance in the past few years” [2].

Based on the needs and applications in each specific field, definitions like reliability, availability, adequacy, dependability and security were specified. The application of these definitions has evolved over many decades, and therefore the usage of some of the terms is unique to the area of power system applications only [2].

Modern society based on its pattern of social, working and also living habits has come to expect the supply to be continously available on demand. This expectation is not physically possible in real life due to random system failures which power system engineers can not control them. The probability of customers being disconnected from electric network can be reduced by more investment during the planning phase, operating phase or both. Preventive maintenance of ageing systems is a vital tool to reduce system unavailability and costs resultant by outages. On the other hand, maintenance actions such as inspections, repairs, replacements etc. bring some additional costs and often increase the unavailability of service [3]. Over-investment can lead to excessive operating costs which must be reflected in the tariff structure. Consequently, the economic constraint will become desecrated though the system could also be very reliable. On the other hand, under-investment leads to the opposite situation. It is evident therefore that the economic and reliability constraints can be competitive, and this can lead to difficult managerial decisions at both the planning and operating phases.

Finding the optimum maintenance policy is seen as coming up with the correct schedule and proper depth of maintenance with the target to maximize the responsibility of the system whereas minimizing the whole price of outages and maintenance actions [3].

These issues have continuously been widely known and understood and it is not suggested that they need solely recently return to the fore. Design, planning and operative criteria and techniques are developed over several decades in an effort to resolve and satisfy the quandary between the economic, operational and reliability constraints [1].

The development of reliability analysis techniques was at the start related to the aerospace industry and military applications. These developments were followed quickly by applications within the nuclear industry. All of those areas have suffered from severe failures in the past. These include aerospace (Challenger space shuttle, 1986; several commercial aircraft accidents annually), nuclear (Three Mile Island, 1979; Chernobyl, 1986) [4], electricity supply (North America, 14 August 2003; Europe, 12 November 2006; Brazil, 10 November 2009) [5], and many similar events in which severe social and environmental consequences and many deaths have been happened. These events have considerably increased the pressure to objectively assess reliability, safety and overall probabilistic risk [4].

2.2 Reliability Data

Data processing comprises two activities:

- Field data collection by operations and maintenance (O&M) personnel documenting the details of all failures as they happen, together with the associated outage duration;

- Analysis of these data to create probabilistic indices, which will be subsequently updated by the access of new data [4].

2.2.1 Data importance in reliability calculations

Any discussion of quantitative reliability analysis invariably results in a discussion of the existence and accessibility of the data needed to support such studies. Valid and helpful knowledge are costly to gather, however it ought to be recognized within the long-term that it will be even costlier not to collect them. It is sometimes argued as "which comes first: reliability data or reliability methodology". Some networks do not collect data because they do not have fully determined a suitable reliability methodology. Conversely, they do not conduct reliability studies because they do not have any data. It ought to be remembered that data assortment and reliability analysis should evolve along, and thus the method is repetitive. The point at which to stop on either should be based on the economic use to be made of the tools, techniques and data [1,4].

The quality of the statistical indices depends on how the data processed, how much pooling is done and how old the stored data are, since these factors affect the relevance of the reliability indices for their future use [1,4]. The quality of the data and thus the confidence that can be placed in it, is directly depend on the accuracy and completeness of the information compiled by O&M personnel. It is thus essential that they must be made very attentively for the longer-term use and also the importance that it will play within the latter developments of the system [1].

It is evident that the best data are one's own data since all related attributes should be known [4]. If these are unavailable, it may be necessary to use generic data collected and analyzed by other organizations. The confidence associated with these data will be lower than the data collected from the one's own utility. In the absence of comprehensive and complete data, it is helpful for an individual utility to gain some consistent criterion using expertise or judgment by which they will then assess the good thing about enlargement and reinforcement schemes [1].

2.2.2 Reliability data collection

One of the main problems relating to data is associated with obtaining the data [4]. At data collection stage, it ought to be remembered that a limitless quantity of data may be collected. It is inefficient and undesirable to gather, analyze and store additional data than is needed for the aim supposed. Therefore, it is essential to spot how the data are going to be used before deciding to gather what kind of data.

Data can be established in one of two ways: from experimental testing or from operational field data. The first is only applicable for small-scale components, which can be tested in sufficient quantities without creating excessive costs. This clearly is an ideal method since data on relevant components are established before they are used in real systems. The second method has to be used for all other situations. These data are then used in subsequent design reviews, creating a feedback loop and a reliability growth concept [4].

Data may be stored in a data bank for later use. In conceptual terms, data can be collected for one or both of two reasons; to assess the past performance whenever needed and/ or to predict the future performance of the system. The past assessment looks back at the past behavior of the system whereas the predictive procedure looks forward at system future behavior. Altogether, it is needed to transform past experience data into the required future prediction. Collection of data is therefore vital as it forms the input to suitable reliability models, techniques and equations [1].

It should also be remembered that the data requirements should reflect the needs of the predictive methodology. This means that the data must be sufficiently general to ensure that the methods can be applied and also restrictive enough to ensure that unnecessary data is neither collected nor irrelevant statistics evaluated. Thus, the data ought to replicate and reply to the factors that have an effect on system reliability and enable it to be sculptural and analyzed. This implies that it ought to relate to the two main processes involved in network component behavior, namely the failure process and the restoration process. It cannot be stressed too strongly that, in making a decision to which data to be collected, a utility must make its decision on basis of the factors that have an impact on its own planning and design considerations [1].

To define reliability terminology and basic data requirements first we have to classified equipments and reliability indices.

2.3 Equipment Classification

Equipments are divided into four different groups with respect to their functions: components, subcomponents, units and terminals.

Component is a device which performs a major operating function and which is regarded as an entity for purposes of recording and analyzing data on outage occurrences. Some examples of power system components are line sections, transformers, ac/dc converters, series capacitors or reactors, shunt capacitors or reactors, circuit breakers, line protection systems and bus sections [6].

Subcomponent is a part or a portion of a component, which is relevant for quantifying exposure to outage occurrences, or failures, or both or for identifying the cause of an outage occurrence or failure [6]. An example for subcomponent is a line segment, which is a portion of a line section that has a particular type of construction or is exposed to a particular type of failure, and therefore which may be regarded as a single entity for the purpose of reporting and analyzing failure and exposure data.

Unit is a group of components, which are functionally related and are regarded as an entity for purposes of recording and analyzing data on outage occurrences [6].

A unit can be defined in a number of different ways. For example, it may be a group of components, which constitute an operating entity bounded by automatic fault interrupting devices which isolate it from other such entities for faults on any component within the group or a group of components protected by and within the sensing zone of a particular system of protective relays for example a transformer or an overhead line and associated terminal facilities switched with it. A unit also can be a group of components including a transmission line, one or more transformers supplied by the line, and a sub-transmission or distribution network radially supplied from the transformer. These components are so configured that the sub-transmission network is in the outage state during outage occurrences of the transmission line [6].

A unit may be single-terminal, two-terminal or multiterminal. A multi-terminal unit is connected to three or more terminals. It is recognized that certain components (for example, circuit breakers) may be part of more than one unit. Different types of units include transmission unit (no different overhead line or cable), transformer unit, bus unit, and special units that consist of any equipment protected by separate breakers, such as shunt capacitors [6].

Terminal is a functional facility (substation, generating station, or load center) which includes components such as bus sections, circuit breakers, and protection systems where transmission units terminate [6].

2.4 Reliability Indices

Component or unit state is a particular condition or status of a component or a unit, which is important for outage reporting proposes [6]. Component or unit has two different states; in-service state or outage state.

When the component or unit is energized and fully connected to the system, it is called in-service state; on the other hand if the component or unit is partially or fully isolated from the system and not in-service state it is called outage state [6]. If the component or unit is completely de-energized or is connected but it is not serving any of its functions within the power system, the component or unit is in complete outage state. If the component or unit is at least partially energized, or is not fully connected to all of its terminals, or both, so that it is not serving some of its functions within the power system, then the component or unit is in partial outage state [6].

2.4.1 Changes in state and outage types

An event involving the outage occurrence of one or more units or components called outage event. An outage event involving only one component or one unit is single outage event. An outage event involving two or more components or two or more units is called multiple outage events. A multiple outage event in which one outage occurrence is the consequence of another outage occurrence, or in which multiple outage occurrences were initiated by a single incident, or both is called related multiple outage events. Each outage occurrence in a related multiple outage event is classified as either a primary outage or a secondary outage depending on the relationship between that outage occurrence and its initiating incident.

An outage occurrence within a related multiple outage event which occurs as a direct consequence of the initiating incident and is not dependent on any other outage occurrence is the primary outage in the related multiple outage event. A primary outage of a component or a unit may be caused by a fault on equipment within the unit or component or repair of a component within the unit. An outage occurrence which is the result of another outage occurrence will be the secondary outage [6].

2.4.2 System reliability calculation

Statistics is the traditional science used to assess the reliability [4]. Two basic types of component data are required for the calculation of system reliability; namely, outage rates and outage durations or switching times. The perfect data required for a specific reliability study depend on the nature and the scope of that study [7].

2.4.3 Rate indices

Outage rates are divided into two different categories; namely, forced outage rates (FOR) and scheduled outage rates. According to IEEE standard, outage rates are obtained by dividing the number of outage occurrences to the service time [6]. The unit of service time in power system reliability calculations usually is one year [6]. Outage rates can be sub-divided by outage types, by the weather prevailing during the service time, or by season.

Forced outages are automatic outages or manual outages that cannot be deferred [6]. As examples of forced outage rates, we can consider persistent-cause forced outage rates and transient-cause forced outage rates. Persistent-cause forced outage is an outage that results from emergency conditions directly associated with a component requiring then it should be taken out of service immediately. A persistent-cause forced outage is a forced outage, which requires the affected component to be repaired or replaced before it could be re energized. If the studied system is a paralleled system and if the effect of the storms is to be considered, persistent-cause forced outage rates should be obtained separately for normal and stormy weather. The units of the outage rates are outage per component per calendar year or per year of stormy or normal weather if the effect of storms is to be evaluated [7]. In the other hand, a transient-cause forced outage is a component outage whose cause is temporary such that the affected part can be restored to service by a reclosing operation or by a fuse replaced. A lightning flashover, which could be cleared by a reclosing operation, is an example of a transient-cause forced outage. Because of the short time duration of most transient-cause forced outages, it seems not to be necessary to separate them into normal and stormy weather catagories. Then the unit of this kind of outage rates is outage per component per service time [7].

A scheduled outage is an outage that results when a component is deliberately taken out of service at a selected time for purposes of construction, maintenance, repair or other work directly associated with or attributable to the component [7]. A manual outage is classified as scheduled if it is possible to defer the outage occurrence without increasing the risk to human life, risk to property or damage to equipment when such a deferment is desirable [6]. Deferring an outage occurrence may be desirable, for example, to prevent overload of facilities or an interruption of service to consumers [6]. The units of the scheduled outage rates are outage per component per service time (calendar year) [7].

Failure rate and protective system false operation rate are other examples of rates. The inability of a component to perform its required function named failure. Failure rate is obtained by number of failures of a particular type divided by exposure time. It should be remembered that failure rates could be computed for a specific component, a class of components or units, or per unit of length in the case of lines, common structure, or common right-of-way exposure [6]. Protective system false operation rate can be established by dividing number of false operations to exposure time [6].

2.4.4 Duration indices and statements

There are different duration indices like mean time to outage or mean outage duration; but first we have to explain some definitions like service time, outage time etc. to have a better view about concept of these indices. The accumulated time one or more components or units are in the in-service state during the reporting period is called service time [6]. The accumulated time when one or more components or units are in the outage state during the reporting periods called outage time and also we know that reporting period time equals service time plus outage time [6]. Outage duration is the period from the initiation of an outage occurrence until the component or unit is returned to the in-service state [6]. It is better to consider that outage duration is normally equal to the sum of switching time, repair time, and travel and material procurement time, but may be longer for reasons other than unavailability of manpower, equipment, or material [6].

The mean time to outage occurrences of a specified type is equal to service time divided by number of outage occurrence of that specified type. In a same way, the mean duration of outage occurrence of a specified type equals to outage time due to outages of a specified type divided by number of outage occurrences of a specified type [6]. Mean outage duration is also referred to as mean time to restoration [6].

Persistent-cause forced outage duration is the period of time from the initiation of an outage until the affected component is repaired or replaced and made available to perform its intended function. Outage duration distribution may usually be satisfactorily represented by mean outage duration. For calculation purposes the units of mean outage durations should be in year [7]. Transient-cause forced outage duration is the period of time from the initiation of an outage until the affected component is restored to service by a reclosing or refusing operation. Therefore, transient-cause forced outage duration is a switching or re-fusing time in fact [7]. Scheduled outage duration is the period of time from the initiation of a scheduled outage until the component is restored to service. Outage duration distributions may usually be satisfactorily represented by mean outage durations. This duration, like persistent-cause forced outage duration, for calculation purposes should have the units of year [7].

Switching or re-fusing time is the period from the time the operation is required due to a forced outage until the operation is completed. Switching times should, in general, include only manual switching times at non-attended locations. Automatic switching times or manual switching times at attended locations can usually be regarded as zero for purposes of system reliability calculations. Manual switching and re-fusing time distributions may usually be satisfactorily represented by mean times. Again, units should be in years for calculation purposes [7].

However, nowadays many other indices are regularly calculated, the most appropriate being dependent on the system and its requirements. It is therefore not reasonable to be prescriptive. Instead, all related indices are now generally termed reliability indices and in consequence, the term reliability itself is frequently used as a generic term describing all these indices instead of being only associated with the probability term [4].

2.4.5 Estimation of outage rates and errors

First of all, it will be usefull to remind that probability theory is the only tool for system engineers which can enable them to transform system knowledge into a prediction of systems future behavior. After exactly obtaining this concept, a model can be derived and the most appropriate evaluation technique can be chosen [4].

To estimate the future outage rate, first step is grouping the lines. This grouping can be based on the voltage level, line structure like shielding, types etc. Second step is plotting the number of outages of a given group of lines for each year per unit length of exposure. It is very important to plot outage number of the lines which, length of exposure not changed during a year and also all data for the whole year are available and also trustworthy. It is not accurate to use outage data of a part of a year and to estimate number of failures of a whole year. It is because the frequency of occurring failures over a year is not uniform and also the number of outages suffered by a line is not necessarily directly proportional to the length of exposure [7].

The next step in data analysis after collecting the data for outage per year vs. line exposure, is determining a mathematical relationship between line exposure and the number of outages per year. Regression analysis can be used in this step [7].

Estimating future outage rates of transmission lines using scatter diagram-regression analysis has advantages like follows:

Scatter diagram of line outages per year vs. line exposure will give us a view to check homogeneity in a homogenous group and after this checking, line which do not act in the same way as the other lines in the group act could be decided to be eliminated or not. Another advantage and also much more important one, the regression method provides a mean for making confidence statements about the line outage rates [7]. It is better not to forget that the outage rate resultant from regression line may be regarded as an estimate of the outage rate in an individual future year or an estimate of the future mean annual outage rate [7].

3. CASCADING FAILURES

3.1 Introduction

Cascading failure is a process in which initial failure(s) in electric power transmission network components may propagate to more widespread outages and cause large blackouts. The initial outages which are already occurred weaken the network and make failure propagation more probable.

Most of the initial failures are because of component reliability and/or external stresses such as weather; while the propagation of outages is more because of overall system resilience. So to mitigate cascading outages, it is necessary either to limit initial failures or the propagation.

The most common rule for reliability is known as N-1 criteria. It means that power system should be able to supply demand even if an unplanned outage occur for any of power network components (transmission lines, underground cables, transformers, autotransformers, generating units and also reactive compensation components) without violating branch thermal limits, nodal voltage limits or whole system stability limits [8]. It is clear that a single circuit fault outage should result no loss of supply from the transmission system. Of course a limited amount of loss of supply is allowed in a fault outage of a double circuit or a single section of a busbar [8]. Power systems always work under a risk of great disturbances, which may lead to blackouts in a large-scale. Network interconnection could increase the system operating efficiency, and obtain a greater economic income. But it also may lead to the increase in the operational uncertainty, interconnecting also makes the system dynamic behaviour more complicated, and expanding the impact of local power grid failure into nearby region electrical network, which is more likely to lead to blackouts caused by cascading failures [9].

A cascading outage is a sequence of events in which an initial failure, or set of failures, lead to a sequence of one or more dependent component outages. In some cases cascading outages stop before the sequence results in the interruption of electricity service in a region. Anyhow in many notable cases, such as blackouts in North America on 14 August 2003, Europe on 12 November 2006, and Brazil on 10 November 2009, cascading outages have resulted in huge disruptions to electricity service. Although such large blackouts are infrequent, they contribute significantly to blackout risk and perceptions of whole electricity service reliability [5].

The cascading outage is influenced by the details of the system state, such as components scheduled outages and the patterns of power transfers, and the automatic and manual system procedures. The initiating events for a cascading outage can include a wide variety of exogenous disturbances such as high speed winds, lightning, natural disasters (hurricanes, earthquakes, etc.), contact between conductors and vegetation or human error. Moreover, there are many mechanisms by which subsequent outages can propagate beyond the initial outages. Generally the dependent component outages occur when relays or humans trip circuit breakers [5].

In a real power system, a significant amount of load shedding caused by dynamic instabilities and voltage collapse due to lack of reactive power are the main reasons leading to cascading tripping of a series of electrical components (generators or branches), which may cause the catastrophic events in system. Catastrophic event sequence, also called collapse sequence (CS), to define this sequence we have to say a series of element disturbence sequences during the system transition from normal operating state to catastrophic event state [9].

Cascading failures of large-scale power grids are rare events that nevertheless pose a grave and likely growing risk to society and also to national security [10]. Cascading failures caused by subtle & difficult to predict combination of individual events such as single line outages [10].

Because cascading failures normally caused by combination of individual events like single line outages and as it is difficult to predict these combinations, recently, considerable amount of researches has tackled the problem of identifying compound contingencies (such as the outage of a few lines in a series) that could place a grid in an unstable condition. This problem is known as ‘N-k problem’ where k integer express the number of simultaneous indivitual events happened in the system. It is naturally a combinatorial problem, which, for the large size of national power system grids, is quite challenging [10].

3.2 Effect of Relays In Cascading Failures

Recent researches show that the power protection system plays a major role not only in any possible initial events, but in further propagation of failures. North American Electric Reliability Council (NERC) studies have also shown that the interval of major disturbances are long and that 70% of disturbances involved the relay system faults, not necessarily as the initial event, but contributing to the cascading failure effect of power transmission system [11].

Over- and under-voltage relays protect most generators while under-voltage relays protect large-capacity load motors and some particular equipments. While in general these relays operate as intended, their operations will reduce the angular and voltage stability margins of the system in the course of a sequence of cascading failures [12].

Impedance protective relays are the most extensively used protective devices in high voltage transmission lines. Generally, the relays operate when the impedance measured by the relays falls within the relays setting range. Unfortunately, they may unnecessarily over trip while cascading failure occur, due for example to voltage sags caused by line overloads. The latter make the measured impedance by a relay smaller than its setting, simulating a nearby fault on the system. Note that among impedance relays, zone 3 relays are the most sensitive to voltage dip due to its large setting range [12].

Most of the incorrect operations display that the relay had an undetected fault that was not observed until abnormal operations occurred, which is often named as a hidden failure [11]. Hidden failure refers to permanent defects that would cause a relay or a relay system to incorrectly and inappropriately react to disturbances. The hidden failures in power system are usually triggered by other events, and not frequently occur, but they may have disastrous consequences [13].

3.3 Tools For Risk Assessment of Cascading Outages

The risk assessment of cascading outage is extremly complicated as it needs exact modeling of a reactions series to an initiating event or events. Considerable efforts have been devoted to develop risk-based tools able to take into account cascading failures. Because of the very huge number of possible events combinations that may lead to a cascading failure, many of these tools adopt a probabilistic approach. Here we will review both the deterministic and the risk-based or probabilistic cascading tools used in power system planning and operation. Then we will describe some of commercially available tools as well as research purpose tools. The available computer programs show considerable differences in many factors, such as load relief, modeling of protection failures, modeling of operating policies, calculated risk indices, etc. A brief summary of commercial and research grade tools used in cascading failure events and their consequences is shown in Table 3.1 and also Table 3.2 [13].

Table 3. 1 : Commercially Available Tools.

Cascading Tool	Methodology	power flow	Max. number of buses	Web address
ACCESS	Analytical + Monte Carlo	DC or AC steady state + dynamic simulation	Practical limit of around 2000 buses	Yes
CAT	Analytical	AC	64,000	Yes
POM-PCM	Analytical	AC steady state + dynamic simulation	No limit	Yes
TRELSS	Analytical	AC or DC	13,000	No

Table 3. 2 : Research-Grade Tools.

Cascading Tool	Methodology	Power Flow	Max. number of buses	Web address
HIDDEN FAILURE, USA	Monte Carlo	AC	300	No
MANCHESTER by The University of Manchester, UK	Monte Carlo	AC	1,500	No
OPA by ORNL-PSERC-Alaska, USA	Monte Carlo, complex system	DC	1000	No
PSA by Los Alamos National Laboratory, USA	Monte Carlo	AC or DC	64,000	No
TAM by Texas A&M University, USA	Monte Carlo	AC	24	No

Now we will describe the tools listed in table 3.1 and table 3.2.

ACCESS is a commercial tool developed by French transmission system operator (RTE), in collaboration with its equivalent in England and Wales, National Grid. It provides a single software environment in which the user can specify, quite precisely, a very wide range of uncertainties, and allow their impact to be explored quite systematically. This is gained by means of four facilities: first of all, a security-constrained AC optimal power flow is used to represent how an operator or the market would have dispatched the available power system facilities. Second, a quasi-steady state simulation - developed between RTE and University of Liege, called ‘Astre' - that, while assuming electromechanical equilibrium of the system, models the action of voltage control devices in particular (and has some simple model of protection of branches of the network). Then, having a full time-domain simulation that allows modeling of many controls on the system, including field current limiters on generators, governors, some forms of generator protection and zone 3 protection on overhead lines. At last Access to a suite of statistical analysis tools that can be applied to detailed simulation results stored for many scenarios in a database [13].

While ACCESS was designed to be applicable in many kinds of study, the possibility of modeling sequences of events, whether independent or consequential to the current state of the system in a simulation, and arying a range of system parameters such as protection settings, line ratings, fault clearance times, etc., provides a powerful means of assessing the possibility of cascading outages occurring and their impact. If the user can have confidence that the specified sampling laws for variation of different initial conditions, equipment parameters and independent fault events are accurate, the probability of different outcomes might also be used in decision making. The downside of such a flexible tool is that it requires specialist users and, especially if a full time domain simulation is to be carried out, considerable volumes of data. A study must also be carefully designed in respect of its specific aims. It must generally be established quite early on whether steady state or quasi steady state analysis will suffice, and, if uncertainties are to be assessed how to define hem so as to concentrate results on areas of interest [13].

Second tool in this category is Cascading Analysis tool (CAT), CAT is a part of the TRANSMISSION 2000® suite of programs developed by Commonwealth Associates Inc. (CAI) and is commercially available. The CAT utilizes TRANSMISSION 2000 software environment to objectively evaluate the potential vulnerability to widespread outages and uncontrolled cascading. The CAT automatically runs a set of contingencies to determine the potential to initiate facility and/or load losses beyond the initial contingency. For each contingency, the tool checks the post-contingency operating state against userspecified criteria. If a subsequent loss is indicated, the tool automatically simulates the loss. The most common criteria that might be used in an analysis are: Thermal Overload Criterion, Low Voltage Criterion and Voltage Change Criterion [13].

For probable events that cause thermal overloads or low voltages, the next outage is specified by looking at thermal violations and identifying the worst overload (as a percent of rating), or, if there are no thermal violations, by dropping load with the lowest actual voltage at the bus. Only one facility is added to the list of outages per iteration. This process is repeated until there are no further criteria violations. For contingencies which cause the power flow to diverge, or if any step is taken to relieve a violation cause’s divergence, load is dropped at the bus associated with the divergence and another attempt is made to solve the case. The process repeats until one of the four conditions is reached:

1. The case solves without violations
2. The next load drop would exceed the user-specified maximum load drop
3. A low-voltage condition is encountered, indicating that load drop is warranted, but there is no load in the vicinity of the voltage violation to drop, or
4. The case interrupts

If the case solves without violations, it means there isn't a reasonable vulnerability to widespread outages. Provided that the probabilities of the initiating events are known and these kind of events as independent, by assuming that the conditional probability that cascading outages cannot be precluded is 1.0, a probability or an index of performance can be computed by summing the probabilities of initiating events [13].

The third tool in the commercially available tools is POM-PCM. Potential Cascading Modes (PCM) tool is a part of Physical and Operational Margins (POM) Suite developed by V&R Energy Systems Research, Inc. and is commercially available. PCM utilizes POM software environment to simultaneously monitor voltage stability, thermal overloads and voltage violations. Execution time for an AC solution for one contingency is approx. 0.1 sec for a 50000-bus case [13]. Initial outages probability are generated either automatically as result of the cluster approach or from user specified probability list [13].

Following an initial failure, cascading chains are automatically identified. A cascading chain is a series of consecutive tripping events following an initial failure which, are caused by overloads exceeding the branch tripping threshold, low voltage or high voltage violation below or above load/generator tripping thresholds. All the thresholds are user-defined [13]. PCM permit the user to analyze the cascading outages as both steady-state and transient stability phenomena. Transient stability approach includes frequency issues and relay operations [13].

PCM has the capability to quickly identify and prevent potential cascading outages in near real-time, operations and planning environments [13].

The last commercially available tool is TRELSS. Transmission Reliability Evaluation of Large Scale Systems (TRELSS) is commercially available tool for reliability assessment of composite generation and transmission systems developed by Electric power Research Institute (EPRI) in cooperation with Southern Company Services. Cascading failure analysis in TRELSS aims to capture the cascade path starting from a strengthened system condition and an initial failure. The user can prepare a list of thousands of initiating events which TRELSS will evaluate each of them separately. A list of threshold values such as the loading level at which a transmission line trips, or the threshold low voltage at which a load is dropped, are set. The model simulates the cascading process as a sequence of quasi-steady state system conditions caused by a sequence of tripping events [13].

A unique feature in TRELSS is the modeling of the protection system actions to realistically simulate potential cascading failures. It is assumed that initiating events are triggered by action of a set of breakers comprising a protection zone. Since several bulk-power transmissions system components are protected by a set of breakers all of these components are taken out of service. A set of components protected by a common set of breakers is termed a Protection and Control Group (PCG). When a PCG goes out of service due to action of the breakers defining the PCG boundary, other components belonging to a different protection zone may also go out of service. In its turn, these initial outages could cause severe overloads and voltage deviations in transmission facilities. This may trigger further tripping action of other PCGs, and so on. Cascading outages can propagate through the interconnection incurring significant loss of load potentially leading to system collapse [13].

TRELSS includes a very fast decoupled power-flow algorithm that implements both partial matrix re-factorization and factor update algorithms to modify the system matrix during bus type switching. Auxiliary solution in the Q-V iteration aids in smoothing solution perturbations introduced due to bus-type switching. These enhancements have resulted in extremely fast solution speed while enhancing the robustness of the solution-algorithm. Within each cascading failure step, generating units are re-dispatched through one of the following methods: unit margin, generating unit participation factor and full or fixed-loss economic generation dispatch. The linear programming module provides a mixed integer solution and incorporates both continuous and discrete controls. Control actions include generator MW and MVAR re-dispatch, transformer tap and phase shift adjustment, capacitor and reactor switching, three classes of load curtailment and even relaxation of area interchange. The remedial actions algorithm is based upon the computation of sensitivity of system constraints, such as overloads and voltage violations, with respect to system controls. The sensitivity computation is exact and utilizes the full Jacobean matrix. User specified remedial actions can be selected such as circuit switching, load transfer or load curtailment when contingencies or system problems occur, and the specification of both study and remedial action areas [13].

First research grade tool is hidden failure. The Hidden Failures (HF) is a research-grade tool developed by Chen and Thorp. HF is based on AC load flow representation with primary focus on modeling of hidden failures thermal overloads and generator re-dispatch. Hidden failures of the protection system are modeled by probabilistic approaches in HF. HF uses fast simulation technique and heuristic random search to identify critical relays that contribute too many possible cascades. The availability of protection data to support simulation and the burden of processing it are issues [13].

Second tool in this catagorie is MANCHESTER. The Manchester model is a research-grade tool which aims to represent a range of cascading failure interactions, including cascading and sympathetic tripping of transmission lines, heuristic representation of generator instability, under frequency load shedding, post-contingency re-dispatch of active and reactive resources, and emergency load shedding to prevent a complete system blackout caused by a voltage collapse. In addition to the standard network data needed to run an ac power flow, the input data consists of probabilities of failures of the generation and transmission components as well as estimates of the probabilities of hidden failures in the protection system. Note that the probabilities of failures can be adjusted to take into account the effect of the weather conditions. One of the distinctive features of the model is that it estimates the time required to restore the load following an outage [13].

The third tool in research grade tools is named OPA. The Oak Ridge-PSERC-Alaska (OPA) is a tool for studying the complex dynamics of an upgrading power system with cascading line outages. OPA represents cascading outages and line overloads with a DC load flow model. Starting from a solved base case, blackouts are initiated by random line outages. Whenever a line is outaged, the generation and load are re-dispatched using standard linear programming methods. The cost function is weighted to ensure that load shedding is avoided where is possible. If any lines were limited during the optimization then these lines are outaged with a fixed probability. The process of re-dispatch and testing for outages is iterated until there are no more outages. The total load shed is, then, the power lost in the blackout. The OPA model neglects many of the cascading processes in blackouts and the timing of events, but it does represent in a simplified way a dynamical process of cascading overloads and outages that is consistent with some basic network and operational constraints. The distinctive feature of the OPA simulation is that it accounts for the complex system dynamics of upgrade so that self-organization of an evolving power system can be studied. Average load slowly increases, lines involved in blackouts are upgraded, and generation is increased to maintain margins and coordinate with the line increases. The simple representation of the cascading and upgrading processes is desirable both to study only the main interactions governing the complex dynamics and for pragmatic reasons of model tractability and simulation run time. The input data for OPA is a DC load flow description of the network, line flow limits, and parameters controlling the probabilistic tripping of lines, average growth rate and upgrading of lines and generation. The output data describes a series of cascading blackouts as the power system gradually evolves, including the lines tripping and load shed in stages of each blackout [13].

Next tool in research grade tools is PCA. The Power System Analyzer (PSA) suite of numerical tools was developed at Los Alamos National Laboratory to permit model building, analysis, and graphical display of electric power transmission networks. With respect to PSA, a model is defined as a geographic representation of an electric transmission network that can be used to compute both linear and nonlinear power-flow solutions that have been benchmarked against a filed base-case solution [13].

The last tool is TAM. The TAM is a research-grade program developed by Texas A & M University. It is a part of general model for reliability analysis developed by Singh and Patton with a particular capability to differentiate various protection failure modes. Two major failure modes in protection system: "failure to operate" and "undesired tripping" are the major cause of cascading outages. The former means that when a fault occurs in a power system, the protection system fails to clear the fault. The later refers to either spontaneous operation in the absence of a fault or trip for faults outside the protection zone. After the initial fault is cleared, power flow in the system would change due to the changing topology. This might lead to redistribution of load on certain lines, which are then risk to trip subsequently. In fact a more explicit model of component paired with protection system is established to include two types of protection failures [13].

4. BRANCHING PROCESS

Networked structures operated under highly loaded conditions are endangered to harmful cascading failures. For example, electric power transmission systems must be designed and operated to reduce the risk of widespread blackouts caused by cascading failure. There is a need for analytically tractable models to understand and quantify the risks of cascading failure in electric power systems. We study a probabilistic model of loading dependent cascading failure by approximating the propagation of failures as a branching process [21].

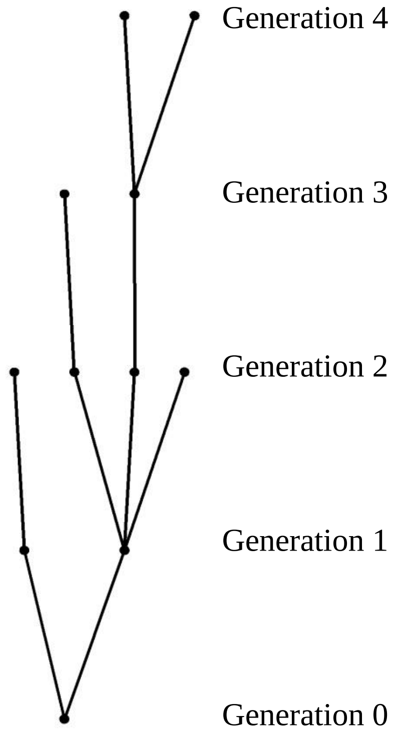

Figure 4. 1: Cascading generations, parents and children.

This diagram explains branching process but does not show location of outages in power grid. Each outage independently has random number of child outages in next generation.

Let p_0, p_1, p_2, ... be the respective probabilities that a man has 0, 1, 2, ... sons, and let each son have the same probability that the male line is extinct after r generations, and more generally what is the probability for any given number of descendants in the male line in any given generation [14]. This question is the base of the Galton-Watson branching process.

Let's imagine objects that can generate additional objects of the same kind; these objects can be men or bacteria reproducing by familiar biological methods, or neutrons in a chain reaction. An initial set of the described objects which we name them 0-th generation, have children which are named the first generation; their children are the second generation, and so on. Do not forget that the process is directly affected by chance events [14].

We give the meaning of number of objects in the n-th generation of a population or family to Z_n [14]. We shal always remember that Z_0 must be equal to 1, unless the otherwise is stated. The appropriate adjustments if $Z_0 \neq 1$ are made as we consider the families of initial objects develop independently of one another [14].

We interpret P as the probability measure for our process. The probability distribution of Z is described by putting $P(Z = k) = p_k,\ k = 0,1,2, \dots,\ \sum p_k = 1$, where p_k is denote as the probability that an object existing in the n-th generation has k children in the (n+1)-th generation [14].

The conditional distribution ofZ_{n+1}, given$Z_n = k$, is appropriate to the assumption that different objects reproduce independently; that is $Z_{n+1}$is distributed as the sum of k independent random variables, each distributed like Z_1. If $Z_n = 0$, then Z_{n+1}, has probability 1 of being 0. Thus, we have defined the transition probabilities of our Markov process, denoted by **(4.1)**.

$$P_{ij} = P(Z_{n+1} = j | Z_n = i), \qquad i, j, n = 0,1, \dots \qquad \textbf{(4.1)}$$

These transition probabilities are defined for each i and j even if, strictly speakingthe right side of equation written above is not defined as a conditional probability if $P(Z_n = i) = 0$.

4.1 Generating Function

We first consider an infinite number of system components. All components are initially unfailed. Component failures occur in stages with Z_i number of failures in stage *i*. We first assume an initial disturbance that causes failure(s) in stage zero. This first failure is considered to cause a certain number of failures Z_1in stage 1. Z_1 is determined according to a probability distribution with generating function $f(s)$. In subsequent stages, each of the Z_i failures in stage *i* independently causes a further number of failures in stage *i + 1* according to the same distribution f(s) [21].

We shall make repeated use of the probability generating function as shown in **(4.2)**

$$f(s) = \sum_{k=0}^{\infty} p_k s^k, \quad |s| \leq 1, \qquad \textbf{(4.2)}$$

Where, s is a complex variable.

Iterates of the generating function $f(s)$ will be defined by **(4.3)** and **(4.4)** [14]:

$$f_0(s) = s, \qquad f_1(s) = f[f_0(s)] = f(s), \quad f_2(s) = f[f_1(s)] \qquad \textbf{(4.3)}$$

$$f_{n+1}(s) = f[f_n(s)], \quad n = 1,2, \ldots \qquad \textbf{(4.4)}$$

It is obvious that each of iterates is a probability generating function, and the relations shown in **(4.5)** are a consequence of above equations [14]:

$$\mathrm{f}_{\mathrm{m+n}}(\mathrm{s}) = \mathrm{f}_{\mathrm{m}}[\mathrm{f}_{\mathrm{n}}(\mathrm{s})], \qquad \mathrm{m}, \mathrm{n} = 0, 1, \ldots, \qquad \textbf{(4.5)}$$

And as specific, shown in **(4.6)**:

$$f_{n+1}(s) = f_n[f(s)] \tag{4.6}$$

The generationg function of $Z_n$is the n-th iterate$f_n(s)$. This basic result was first discovered by WATSON (1874) and has been discovered a number of times since then [14].

4.2 Survival of Animal Families or Genes

We will now fix our attention on a family descended from some one member. Suppose that the family has an average multiplication rate of λ, which, may be different form 1 to some reasons [14].

The mathematical treatment of branching process is simple as the reproduction of an object is supposed to be independent of past history and also from present situation of other objects. Once the assumption of being independent dropped, there is no simple way of classifying the resulting process. They may be Markov or non Markov processes of quite general types [14].

4.3 Cascading Processes

Branching processes have long been used in different applications to model cascading processes, but their applications to the risk of cascading failure is recent. The Galton-Watson branching process gives a probabilistic model of the number of failures [15]. Branching process models are an obvious choice of stochastic model to capture the great features of cascading blackouts, because they have been developed and also applied to other cascading processes like genealogy, epidemics and cosmic rays [16].

There are general arguments supporting the choice of a Poisson distribution for the offspring distribution [14]. The Poisson distribution is a good approximation when each failure propagates to a large number of components so that each parent failure has a small, fairly-uniform probability of independently causing child failures in a large number of other components. This assumption seems reasonable for cascades in power systems, especially in the initial part of the cascade when there are many unfailed components which are stressed by the components already failed [15].

We assume an arbitrary distribution of nonzero initial failures $\mathrm{P}[\mathrm{Z}_0 = \mathrm{z}_0]$ for $\mathrm{z}_0 = 1, 2, 3, \ldots$. Then it is a standard result in branching process that the total number of outages is distributed through a mixture of Borel-Tanner distribution [14].

4.3.1 Borel-Tanner distribution function

The Borel-Tanner distribution (Tanner-Borel distribution) of Tanner (1953) describes the distribution of the total number of customers served before a queue vanishes given a single queue with random arrival times of customers (at constant rate *l*) and a constant time (β) occupied in serving each customer. If there are initially n customers in the queue, then the probability that the total number (Y) of customers served before the queue vanishes is equal to y is calculated from **(4.7)** [18]:

$$P_r[Y = y] = \frac{n}{(y-n)!} y^{y-n-1} (l\beta)^{y-n} e^{-l\beta y}, \quad y = n, n+1, \ldots \qquad \textbf{(4.7)}$$

The case $n = 1$gives Borel distribution; this was obtained by Borel (1942). The parameters l and β appear only in the form of their product $l\beta$. It is convenient to use a single symbol for this product and to put $l\beta = \lambda$ [18].

5. FAILURE PROPAGATION ESTIMATION FOR TURKISH NATIONAL POWER TRANSMISSION SYSTEM-THRACE REGION

5.1 Turkish National Power System, Thrace Region

Turkish electricity transmission system has a total transmission capacity of 95000 MVA and is operated by Turkish Electricity Transmission Company (TEİAŞ) [19]. Its splitted up into Transmission, Installation&Operation Group devisions. Thrace part of Turkey consists of 2 out of 22 devisions; namely, 1st and 21th Transmission, Installation&Operation Group devisions in Davutpasa and Edirne, respectively. This study covers the regions included in those two regions, since Thrace part was a single devision in the past. Thrace part of Turkish National Power Transmission System is the most power consuming region of Turkey (30-35%) [19]. In this area, the electrical network contains both the 154 kV and 380 kV high voltage levels. The transmission network consists of several types of transmision lines (2C, 3C etc) and several types of high voltage underground cables (K100, K1600 etc). Table 5.1 illustrates the number of main components in this sample transmission system. Calassification of the components is done according to TEİAŞ data collection scheme.

Table 5. 1: Number of electrical components in Thrace network.

Component type	Number of components
380 kV transmission line/cable	22
154 kV transmission line/cable	111
Power transformer	109
Autotransformer	11

Figure 5.1 shows the geographical lay-out of TEİAŞ-Thrace power transmission network. In the figure, red lines and black lines show 154 kV, and 380 kV power transmission lines/cables.

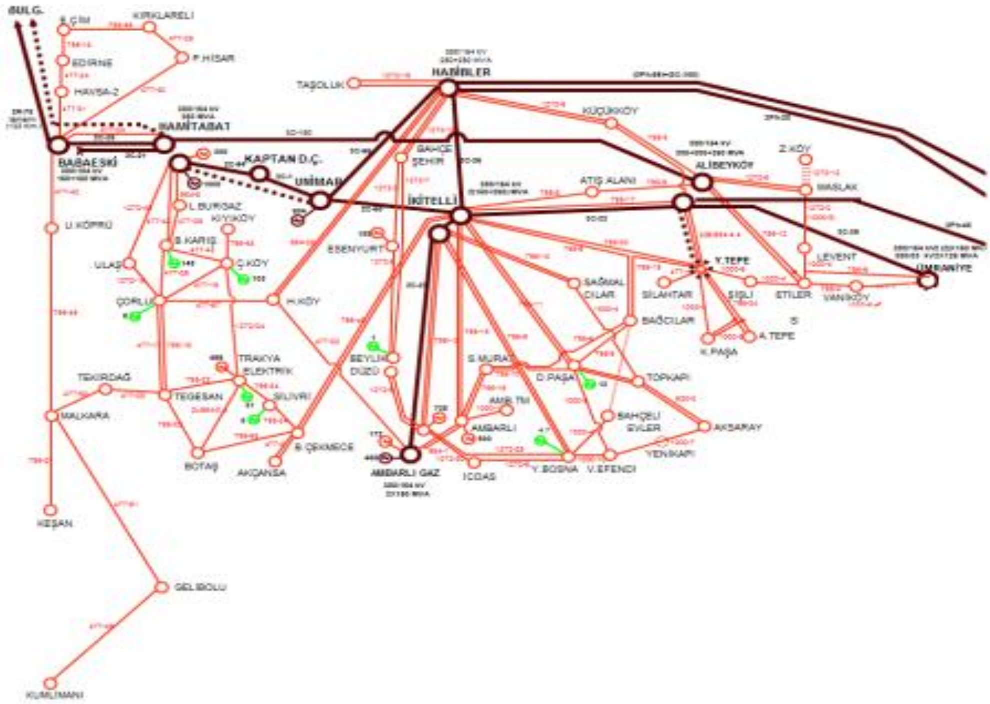

Figure 5. 1:TEİAŞ-Thrace power transmission system.

5.2 Data Set

Past records showed that the number of outages in Thrace part of Turkish National Power Transmission system was more than it was expected and more than the number of outages at the other parts of the system [19]. The study used 7-year duration operational data belonging to 2000-2006 provided by TEİAŞ authority. Outage data includes the outage time and repaired time to the nearest minute for each outage. In addition, data includes atmospheric conditions, shedded loads, failure reasons and failure types for some otages.Sample outage data sheet is shown in Figure 5.2

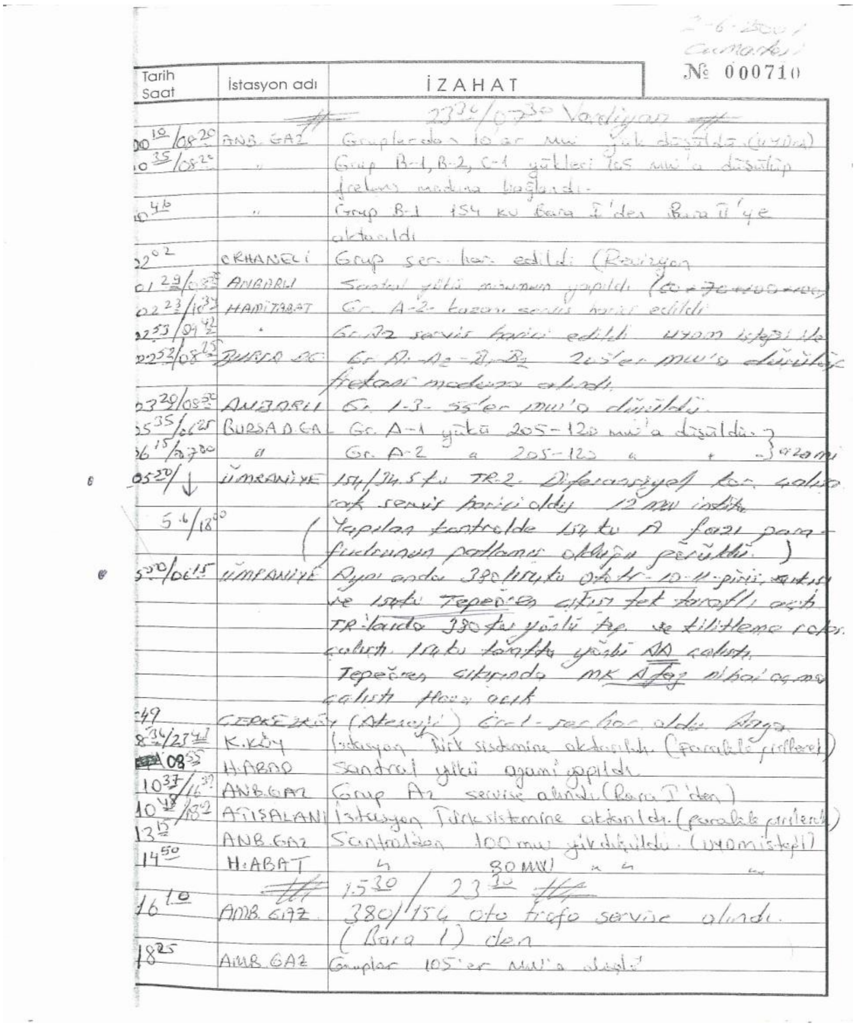

Figure 5.2 : Sample outage data-sheet used in the studies.

Transmission line/cable outages include both the failures occurred along the transmission lines/cables and the station oriented failures at both terminals. There were totally 4320 outages recorded by TEİAŞ staff over the 7 years [20]. The number of total outages for each year is shown in Table 5.2. These data include the transmission lines and cables (380 kV and 154 kV), power transformers and autotransformers. A detailed single and multiple outage statistics in for the region is reported in [19].

Table 5.2 : Number of outages in each year.

Year	2000	2001	2002	2003	2004	2005	2006
number of outages	654	817	557	645	755	156	736

5.3 Grouping Outages into Cascades and Stages

At the first phase of outage propagation study, it is necessary to group the outages into different cascades, and then seperate these cascades into different stages. Classification is done with respect to outage and repair timings and it is not based on the relation between the single outages.

Outages starting within one hour time period and finishing (taking back into service) time differences are not more than 2 hours are accepted to be in the same cascade. These time segmentations are arbitrary and it can be shown that it doesn't have significant impact on the final propagation rates. On the other hand, outages starting within the same minute are classified as belonging to the same stage in the cascade. It is obvious that such a classification does not include temporary outages which are generally fixed within in a minute.

5.4 Branching Processes

With assumption of arbitrary distribution of nonzero initial failures ($Z_0 \neq 0$) it is a standard result in branching processes that the total number of failures Y is distributed according to Borel-Tanner distributions.

5.5 Estimating Cascading Outage

Borel-Tanner probability mass function was given in (4.7) as,

$$P_r[Y = y] = \frac{n}{(y-n)!} y^{y-n-1} (l\beta)^{y-n} e^{-l\beta y}, \quad y = n, n+1, \ldots \qquad \textbf{(5.1)}$$

This function with n=1 will be used to estimate cascading outage as bellow:

$$P[Y = r] = \sum_{z_0=1}^{r} P(Z_0 = z_0) z_0 \lambda (r\lambda)^{r-z_0-1} \frac{e^{-r\lambda}}{(r - z_0)!} \tag{5.2}$$

It is obvious that we will have $P[Y = 1]$ like shown in (5.3):

$$P[Y = 1] = P[Z_0 = 1] e^{-\lambda} \tag{5.3}$$

In theese functions, total number of failures Y is the sum of Z_is.

$$Y = Z_0 + Z_1 + \cdots + Z_r \tag{5.4}$$

$Z_i$is number of failures in i-th stage of the cascade. $Z_0$is the initial outage number before cascades start.

Average propagation rate is shown by λ, sufficient condition for (5.2) is $0 \leq \lambda < 1$. To calculate λ, bellow equation will be used:

$$\lambda = \frac{\sum_{k=1}^{K} \left(Z_1^{(k)} + Z_2^{(k)} + \cdots \right)}{\sum_{k=1}^{K} \left(Z_0^{(k)} + Z_1^{(k)} + \cdots \right)} \tag{5.5}$$

Note that λ shows the propagation rate and is different from failure rate. This rate shows how outages in any stage propagate to the next stages.

$Z_j^{(k)}$ in Eq. 5.5 show the number of outages in stage j of cascade k.

The empirical distribution of Y can also directly be obtained from the utility data by using Eq. (5.6).

$$P_r[Y = r] = \frac{number\ of\ cascades\ with\ total\ r\ outages}{total\ number\ of\ cascades} \tag{5.6}$$

To test how well the branching process model describes the data, first we use (5.2) and calculate λ from (5.5). This calculation shows how the distribution of initial outages used to predict the distribution of the total number of outages Y. Then, λ will be calculated empirically using (5.6). Finaly, the two failure propagation rates will be compared. The probability of cascade starting with z_0 initial outages is calculated from (5.7).

$$P[Z_0 = z_0] = \frac{number\ of\ cascades\ with\ Z_0 = z_0}{number\ of\ all\ cascades} \quad \textbf{(5.7)}$$

In our study cascades contain transformers, autotransformers, overheadlines, cables. According to 7-year outage data, there are totally 524 cascades. Λ, calculated for each year is as shown in Table 5.3.

Table 5.3 : λ for each year calculated from utility data.

Year	2000	2001	2002	2003	2004	2005	2006
λ	0.189	0.163	0.118	0.144	0.147	0.057	0.11

As seen in table 5.3, λ gets the smallest value in 2005 for the study period. There are big differences between this minimal propagation rate and the other propagation rates. Actually, this case is originated due to minimum number of failures in 2005 (see Table 5.2). The result can be stated as, less number of annual failures generally give low values of propagation rates.

The average propagation rate for the 7-year period is0.1428

Initial outages distribution using (5.7) is shown in table 5.4.

Table 5.4 : Initial outage distribution.

Z_0	1	2	3	4	5	6	7
$P(Z_0)$	0.879	0.081	0.022	0.007	0.004	0.003	0.001

Table 5.5(continue)

8	9	10	11	12	13	14	21
0.0003	0.0006	0.0006	0.0006	0.0003	0.0003	0.0003	0.0003

Empirically calculated probabilities of total line outages (P_r) using TEİAŞ utility data and (5.6) will give result like table 5.5.

Table 5.6 : Empirical $\boldsymbol{P_r}$ using TEİAŞ data.

r	1	2	3	4	5	6	7	8	9	10	11	12	>12
P_r	0.827	0.097	0.031	0.014	0.007	0.005	0.003	0.001	0.002	0.002	0.002	0.002	0.004

As P_r is getting too small after 12 outages, more than 12 outages is considered in cumulative form.

Using table 5.3 and λ calculated above we will have estimated P_r by using (5.2). Results are shown as in table 5.5.

Table 5.7: Estimated $\boldsymbol{P_r}$.

r	1	2	3	4	5	6	7	8	9	10	11	12	>12
$P[Y=r]$	0.762	0.155	0.047	0.017	0.007	0.005	0.002	0.001	0.0007	0.0006	0.0005	0.0005	0.0003

Comparing estimated and empirical P_r(table 5.4 and table 5.5) we have an average error of 23.12% for the first 8 stages.

Comparing estimated and empirical results for P_r are shown in Figure 5.3 in detail.

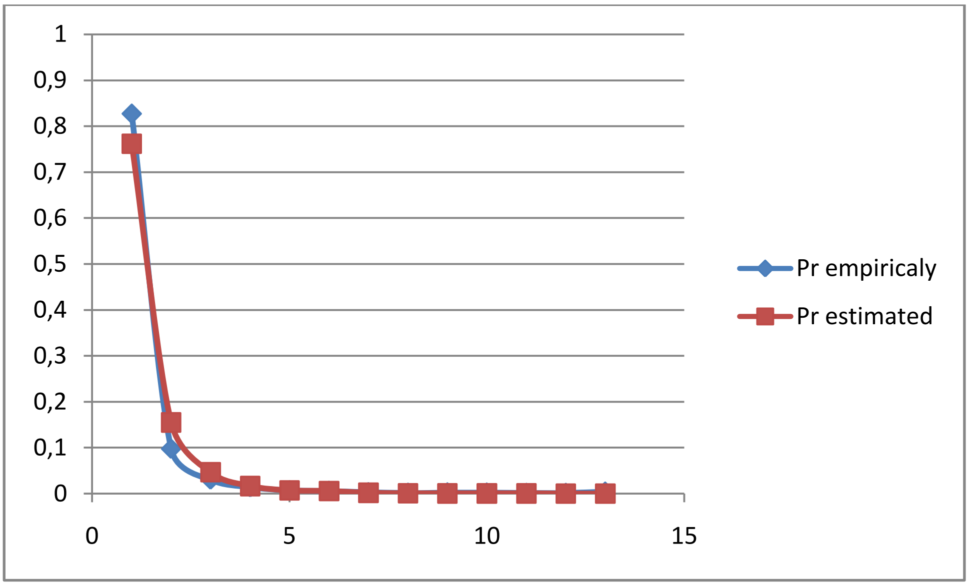

Figure 5. 3 : Comparison empirical and estimated P_r.

6. CONCLUSIONS AND RECOMMENDATIONS

We consider cascading transmission line outages observed in 7 years of operation of a power system explained at 5.1, by describing components bulk statistical behavior rather than the details of individual cascades. In this study, the branching process calculations bulk all the outages together, in future works it will be better to divide outages into different categories, for example initial outages can be sorted into two different categories like little or no propagation probability outages and high probability of propagation outages.

We group the outages into cascades and stages according to their outage times and then estimate the average propagation of the outages (λ). For this data, the empirical distribution of the total number of outages are well approximated by the initial outages propagating according to a branching process with propagation parameter λ. In particular, this data supports the validity of the branching process model for prediction of the distribution of the total number of outages. As the propagation parameter lambda may be highly variable depending upon system loading and generation dispatch, the branching method averaged over time and over the area over which the data was collected. In this study outages occurring within a certain time interval were considered to be dependent outages and the location of the outages has no role in considering dependence.

Hui Ren and Ian Dobson at [15] calculate λ just for lines whereas in this study we do same calculation for transformers and autotransformers beside the lines. Average propagation of the outages in [15] is equil to 0.25 but in our study is about 0.14 which means each outage in the network produces an average of λ=0.14 outages in the next stage. This result is less than λ calculated at [15] considering in this study we calculate this λ considering all network components but in [15] they just calculate it for lines. Note that region considered in this study is much smaller than region considered at [15]. The probability distribution of total outages in cascades are also predicted and it has about 23% error in comparison with empirically results shown in table 5.4, this error is calculated for first 8 stages which are more populated.

In this study we use branching process to predict the probability distribution of the size of cascading outages using industry data, when the initial outage distribution is known. Obviously for more accurate results we need data for more years and of course data gathered with more detail will help to produce more accurate results.

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