Measuring Turkish System Security Using Thermal Security Index

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Abstract

In fast growing electricity networks such as the one in Turkey, it is vital for long term investment plans to be done after careful investigation of the existing system situation. As an investment indicator, in this paper, Thermal Security Index (TSI) method is applied to the data of expected Turkish Grid system 2013 Summer Peak including the load flow solutions of the outages of the 400 kV and 154 kV transmission lines and the 400 / 154 kV autotransformers, resulting in total number of 1867 contingencies. For each contingency, the effect of the outage on the other elements are monitored, accumulated, and ranked according to its TSI. In addition, to gain insight about the regional problems of the network, for each region in Turkey, the average effect of an outage is calculated which is directly related with the undesirable load shedding values for both network operator and citizens. As a result, a very useful indicator for determining the future investments plans for transmission system is presented.

1. Introduction

Turkey is one of the fastest growing markets, with 9.2% and 8.5% growth rate in 2010 and 2011 respectively [3]. Electricity sector is also growing steadily with economic growth and population. There is an increasing demand in energy and there are many generator companies that would like to invest in Turkey [4]. As a result, there is a need for systematic grid expansion planning process in order to meet the demand of both.

From static point of view, network security should include following conditions:

- There is no loss of load,
- The bus voltages are in acceptable limits,
- The flow of the lines do not exceed the thermal limits and,
- System operation is at a safe margin from static voltage collapse.

In addition, the system should be designed such that it can withstand and operate in N-1 and certain critical N–2 contingencies with above-mentioned conditions. [5]

It is common today for electric power transmission system planning horizons to be 10 years or less [6] since uncertainty about the development of future generation and investments exists for long-range transmission planning. As a result a long term investment plan should both include solutions of problems in existing system and a future operation scenario which includes effect of possible future generation and demand centres. In planning, contingency analysis during periods of high demand is used in the long-term design of system expansion [6].

In the following section, the methodology used in order to indicate the existing network problems, TSI is defined and then in the third section, expected Turkish Grid in Summer-Peak 2013 is examined in terms of static system security and contingency analyses using TSI. The designed algorithm inputs the static system data, and then by AC contingency analyses, it outputs contingency loading matrix in addition to printing individual TSIs. In the last section possible future development studies are mentioned.

2. Thermal Security Index

This section describes a contingency analysis-based method to measure system security and rank transmission elements by their relative "weakness." The "weakness" of a transmission element is an indicator of the need to upgrade branch or to design system expansion to avoid thermal security violations under specific conditions [1-2].

In the methodology, for contingency analysis, each possible outage is performed, the AC power flow is solved, and the branch flow violations are tabulated. Each branch is listed for contingencies that caused overloads in that particular branch, together with the violating flows and percentages, as shown in Table 1.

Table 1. Example of Contingency Results in Summer 2013

Branch	Limit (MVA)	Contingency Label	%
422121 to 622221(1)	132	410511-612711(1)	107
		612721-622121(1)	103
		621521-622121(1)	106
120321 to 121821(1)	360	120821-122021(1)	102
		120910-120921(1)	106
:	:	:	:

The used indicator, which includes both the effect of severe contingencies and multiple loadings, is defined as follows: P_{CO} is the MW overload that appears in a line when a contingency occurs. If there is no overload, then P_{CO} is zero. Here stands P for active power, and the subscript $_{CO}$ indicates contingency overload.

$$P_{CO}, \text{BRANCH jk [MW]} = (\%\text{Overload} - 100) \text{x MVA Rating}_{\text{BRANCH jk}} \quad (1)$$

Equation (1) makes the approximation that the MVA rating of the line is also MW limit. This is commonly done in linear methods and in the DC power flow [1]. The main aim of this approximation is to include the effect of reactive power flows while representing P_{CO}.

P_{ACO} is defined as the sum of the overload for all contingencies that caused overloads in a transmission element during the set of contingencies. The subscript $_{ACO}$ stands for aggregate contingency overload. For instance the total overload of branch 422121 to 622221(1) in Table 1 is equal to $7 + 3 + 6 = 16\,\%$, resulting the P_{ACO} value of Branch $\frac{16}{100}\,x\,132 = 21.12\,\text{MW}$. Therefore, for a transmission element, P_{ACO} is calculated as:

$$P_{ACO},\text{BRANCH jk [MW]} = \sum_{Cnt} P_{CO},\text{BRANCH jk [MW]}$$

$$\text{Cnt} \in \text{Contingencies that overloaded Branch jk} \qquad (2)$$

This quantity can also be expressed in percentage, but it is useful to use it in MW. Expression in MW is a superior index compared to the percentage quantity, because it contains information about the MVA flow in the line. For instance, while calculating the overloads of the lines, 20% overload in a 154 kV line should have lower severity than 20% overload in a 400 kV line. The branch P_{ACO} has the following properties that make it useful for defining the weakness of a branch:

1) If a branch is not overloaded for any contingency in the contingency list, then its P_{ACO} is zero.

2) P_{ACO} is high if a branch is either severely overloaded for a few contingencies or lightly overloaded for many contingencies. The value is very high if the branch is severely overloaded for numerous contingencies.

3) The higher the P_{ACO}, the weaker the branch.

Since the P_{ACO} can be computed for every line in the system, a system contingency overload metric P_{ACO}^{SYS}, can be defined as the sum of each branch:

$$P_{ACO}^{SYS} = \sum_{Branches\ jk} P_{ACO},\text{BRANCH jk} \qquad (3)$$

In the case of large-scale systems like in Turkey, it is better to use a similar index for each area in order to distinguish the effects of the transmission line loadings in different areas. Since Turkish grid system is a large network containing more than 3600 buses and 4600 branches, in the conducted study, 9 Turkish Regional Load Dispatch Centres (RLDC) are utilised as control areas.

The P_{ACO}^{AREA} will consider all the lines inside each area, plus half of the each tie line:

$$P_{ACO}^{AREA\ i} = \sum_{jk} P_{ACO},\text{BRANCH jk} + \sum_{tl} \frac{P_{ACO},\text{BRANCH tl}}{2}$$

$$\text{jk} \in \text{Branches inside Area i,}$$
$$\text{tl} \in \text{Tie lines of Area i} \qquad (4)$$

Although the $P_{ACO}^{AREA\ i}$ provides a metric of the security of areas, it is high not only for highly loaded areas but also for large areas which contains many transmission elements. Therefore, in order to make the metric independent of the size of the area, the metric can be divided by the total number of branches inside the area and the tie lines. The thermal security index (TSI) of an area is defined as:

$$TSI_{AREA\ i} = \frac{P_{ACO}^{AREA\ i}}{N_{Branches\ of\ Area\ i}} \qquad (5)$$

This $TSI_{AREA\ i}$ metric represents the average MW overload expected in a line during contingencies. This is also directly related with the unsatisfied demand during contingencies, since in order to prevent the overloading of the network elements and to satisfy system security in short range, load shedding will be done [1].

3. Numerical Results

The methodology is tested on the expected Turkish network in summer peak 2013 in order to evaluate the system security. The network has 3678 buses, 9 control areas and total 4695 transmission elements (branches and transformers), as shown in Fig.1 and Fig. 2 respectively. The colors of the elements in Fig. 2 stand for the voltage levels of the transmission network.

The designed algorithm inputs the network data and for every network element outage, it performs AC Contingency Load Flows. After each flow, all the remaining elements are monitored and thermal loading effect (P_{CO}) of deficiency of that element is stored resulting in an N x N matrix where N being the total number of network elements in the system. Since the resultant matrix is a sparse matrix (most of the elements are zero), it is easy to store and analyse the results. The system outputs can be used in long term planning as well as in short term decision since in a case of failure, a quick decision can be made whether there is a need for load shedding by looking at the resultant matrix.

Fig. 1. Turkish Grid System: 9 RLDCs and Transformer Substations

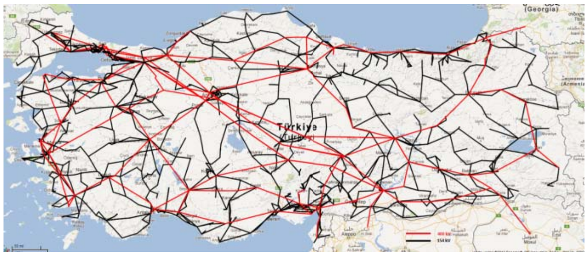

Fig. 2. Turkish Grid System: Year 2013 Existing Transmission Lines (as the crow flies)

In the normal operating load flow solution for the summer peak 2013 (base case), the total numbers of the loaded transmission elements case is 11. The loaded transmission elements are shown in Table 2. Later, these weak lines will be compared with the P_{ACO} value and the total number of the loadings of the branch.

The weakest element in the base case is line 110221 to 111221(1) with a loading of 111%. As the simulation is utilised for peak demand, it can be assumed that system can be operated with those loadings without load shedding. However, a load flow solution in which there exists a line whose loading is greater than 120% of its rating is not a feasible solution. As a result, during the contingency analyses if such a case occurs, the contingency is regarded as there is no convergence in the load flow solution, and handled in a different manner as will be explained later.

Table 2. Turkish Grid System 2013 Summer Peak Solutions: Loaded Transmission Elements

Branch	V (kV)	Area	Loading %
110221-111221(1)	154	1	111,01
220022-220721(1)	154	2	107,10
120421-121322(1)	154	1	106,82
612521-612821(1)	154	6	106,62
424621-612821(1)	154	4	104,09
210321-212521(1)	154	2	102,61
621521-622121(1)	154	6	102,20
110821-113621(1)	154	1	101,92
813121-814121(1)	154	8	101,75
110221-113621(1)	154	1	101,58
213721-220821(3)	154	2	100,00

The first procedure of the TSI analyses is performing the contingency analyses for each element and finding their P_{ACO}, BRANCH . Firstly, the AC load flow is performed on the expected Summer Peak in 2013 case file which is defined as Base Case. The Base Case Results of the system is printed in order to give a first insight about the overall existing network security of the system. Then using the contingency list, which consists of all 400 kV and 154 kV lines and 400 /154 kV autotransformers, N-1 analyses are performed and the calculated P_{CO}, BRANCHs are added to P_{ACO}, BRANCH. The 66kV network is not included in the analyses since they would be upgraded in the near future.

While performing the contingency analyses, it is also checked that whether an outage of the line leads to an “infeasible solution”. Infeasible solution regards to a situation whether the AC static load flow solution is divergent, or there exists a line which is loaded higher than its critical loading. (circuit breaker openings). It means that the system cannot survive in that contingency, the existence of Branch_{jk} is vital for that case. In order to include that conclusion in the analysis, for that particular contingency of Branch_{jk} the Pco is included for only the branch itself as 100%, and the branch name is outputted. For the other feasible contingencies, the *P*co is calculated for each network element. At the end of the contingency analyses P_{ACO}, BRANCH for each transmission element is calculated using the equation (2) and the output is printed. Figure 3 represents the flow chart of the P_{ACO} analyses.

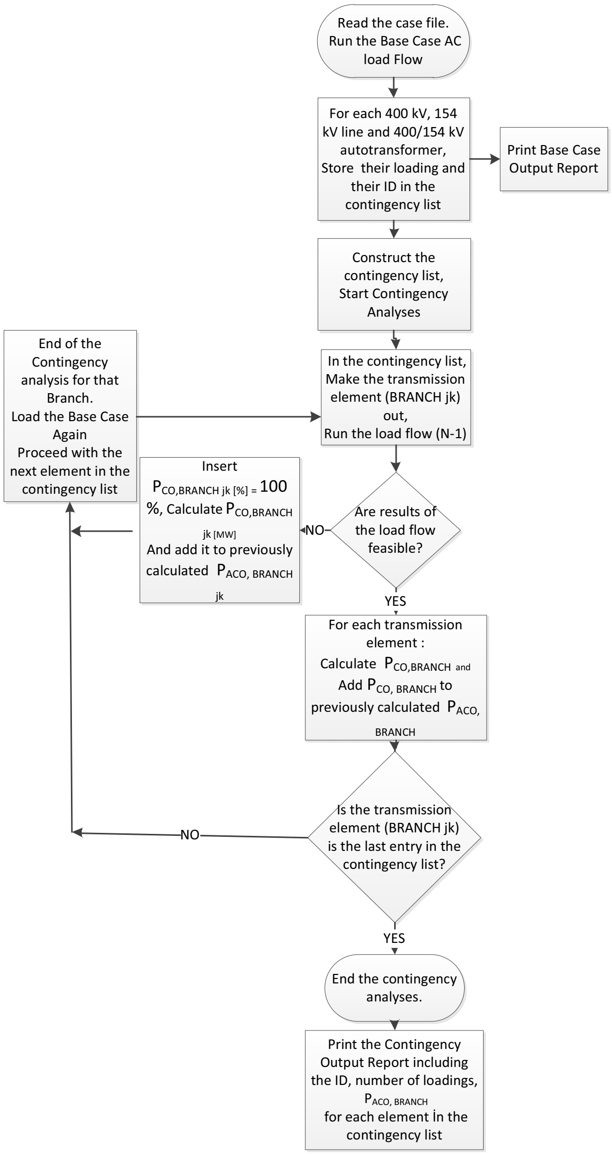

Fig. 3. Flow Chart for the $P_{ACO}, BRANCH$ Calculation Procedure

The top twelve of the “weakest” elements, in other words the elements which have the biggest P_{ACO} value is given in Table 3. Comparing the number of loadings with the number of contingency analyses which is 1867, one can conclude that in the most of contingency analyses, these transmission elements are overloaded except the 400kV line. It is expected since these lines are already over-loaded in the base case. For the 400 kV line, although the number of contingencies that overload the branch is low and it is not overloaded in the base case, the contingency overloads in MW are high, meaning that necessary investment for the branch is as important as the others.

In Figure 4, the output summary is given: It can be seen that 10 lines (the ones that are overloaded in the base case) are overloaded in more than 85% of the contingencies (more than 1600 times in 1867 contingencies) and 112 lines are overloaded only in a single contingency. It can be stated that, double circuiting of the single time loaded elements or re-dispatching generating units can be solutions in the latter case, while more complex analyses and investments are needed for lines which are loaded more than a few times. In addition to weakest elements report, the developed algorithm outputs that outage of 111121-111421(1) line leads to an infeasible solution. When system configuration is investigated, it is seen that outage of the mentioned element leads to a configuration in which many Transformer Substations become radial and due to severe voltage drop, the solution diverges, making an investment necessary.

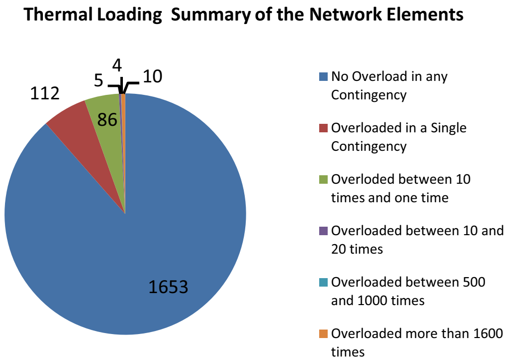

Fig.4. Thermal Loading Summary of the Monitored Network Elements

Table 3. Turkish Grid System 2013 Summer $P_{ACO}, BRANCH$ Analyses: Weakest Transmission Elements

Branch	V (kV)	Area	Paco_MW	Number of Loadings
110221-111221(1)	154	1	31728,21	1671
120421-121322(1)	154	1	17579,50	1669
220022-220721(1)	154	2	13167,18	1668
612521-612821(1)	154	6	12317,42	1666
424621-612821(1)	154	4-6 Tie Line	7675,11	1660
210321-212521(1)	154	2	7115,94	1662
621521-622121(1)	154	6	4358,71	1644
110821-113621(1)	154	1	3903,45	1664
110221-113621(1)	154	1	3278,72	1664
813121-814121(1)	154	8	3202,27	1673
214210-214810(1)	400	2	800,14	4
213721-220821(3)	154	2	471,84	659

Comparing the overloaded elements in the base case and the results of the analyses, one can see that, a new line is added to the weakest elements and the rankings in the lists are changed. This shows while determining the overall importance of the lines and considering the system security, the analyses of P_{ACO} are very useful to decide the starting investments in the first stage. P_{ACO} is very useful in determining the needs in the transmission investments. Planners can use the metrics to identify and rank weak elements and design transmission expansion alternatives.

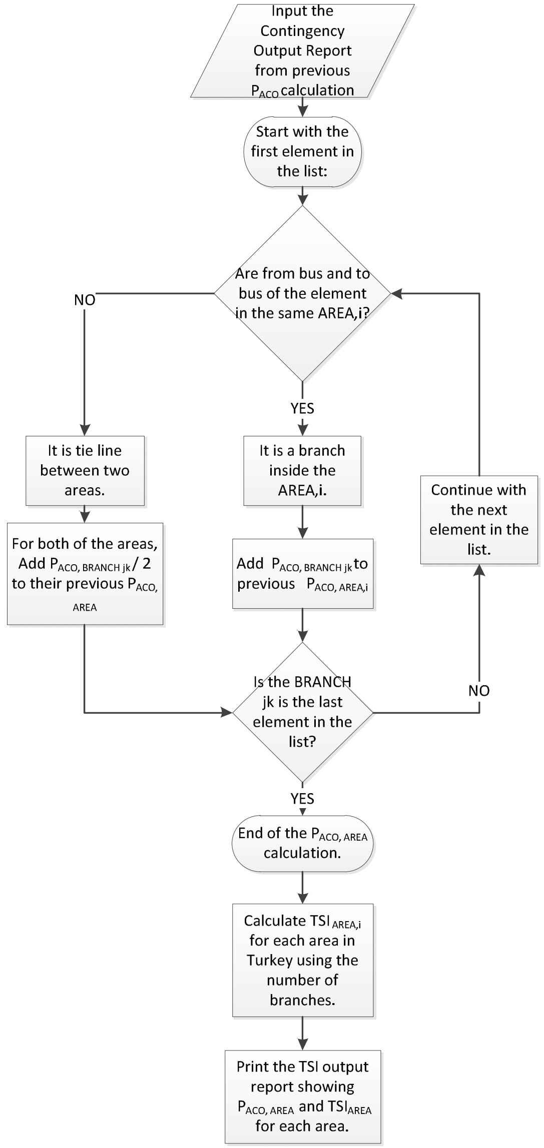

Fig. 5. Flow Chart of the TSI Algorithm

After calculating P_{ACO}, BRANCH, the remaining part of the TSI system analysis is the calculation of the $P_{ACO}^{AREA\ i}$ and $TSI_{AREA\ i}$ for each RLDC in Turkey to have information about regional needs. To accomplish that, first, the designed algorithm inputs the output report in the previous P_{ACO} calculation. By looking the areas to which the from and the to bus of the branch belongs, the algorithm decides whether it is an element inside the area or it is a tie line between the two areas. Then, according to equations (3) and (4) P_{ACO} of the branch is added to previous P_{ACO}^{AREA} sums. At the end of the procedure, TSI_{AREA} is calculated using Equation (5), and the results are printed. The flow chart of the calculation is given in Figure 5.

Table 4. Turkish Grid System 2013 Summer TSI_{AREA} Analyses: Output Report

Area	Paco_Areas	Number of Elements in the Area	TSI_Areas
1	57886,26	174	332,68
2	23262,33	298	78,06
3	765,17	273	2,80
4	4558,46	220	20,72
5	193,33	158	1,22
6	21529,70	167	128,92
7	788,94	140	5,64
8	6875,07	314	21,90
9	2045,82	201	10,10

As expected from Turkish electricity network, the biggest P_{ACO}^{AREA} belong to the first region, which has considerable amount of demand. In addition to that, second region, which is in between the demand and generation centres and sixth region, in which there are many hydroelectric power plants, have large TSI values. Area 5 has the lowest P_{ACO}^{AREA} value which is followed by Area 3 and Area 7. The low values in Area 5 and Area 3 can be explained by balanced generation & demand profile and sufficient transmission elements and while for Area 7, it is resultant from the low generation and demand in the area and remoteness from load centres. Dividing P_{ACO}^{AREA} value with the number of the contingencies can give an insight about the average MW overload of the system during a single contingency.

In the overall TSI calculation, the biggest value belongs also to first region. TSI value represents the sum of MW overload in a line in that region during all contingencies. Therefore one can conclude that an average over-loading of a line in first region is higher than other regions. Therefore, as a planer it is better to start investments from First Region considering the overall system security and the social welfare. Because, TSI values are also directly related with the unsatisfied demand, in other words load shedding due to transmission congestion. They indicate the load decrement value needed to be system be in the normal operation state. It can be said that the higher the TSI of the area is, the insufficient the transmission elements in the areas are in order to supply that demand. As a result, the higher the TSI, more demand cannot be satisfied due to congestion and it is an undesirable situation for both Transmission system operator (TSO) and the citizens.

4. Future Works

As a future work, it is possible to add the probability for each of the contingencies in the system security analyses while calculating P_{ACO}. For instance, the probability of a failure of an underground cable is much lower than those in overhead lines; as a result the outage of first one should have less importance while deciding the system investments.

In addition to that, in a similar manner as in the case of monitoring the overloaded transmission elements, a bus voltage monitoring can also be added to the contingency analyses. By this way, the likelihood of voltage collapse matrix can be constructed and it can lead the way for deciding new transforming substations and transmission elements.

Lastly, this work can be done for different seasons and days in order to represent the current system in any dispatch of the generating units. However, it is expected that analyses in the peak conditions will be dominant.

5. Conclusions

In this paper, an algorithm designed in order to apply the TSI methodology which gives insight about long term investment places and electricity system's bottleneck. The algorithm is illustrated with a case study in Turkish network system in expected 2013 Summer Peak data. The calculated P_{ACO} and TSI values are observed to be very good indicators in order to give insight about the starting points of the investments since they are directly related with the unsatisfied demand. The loss demand means the loss of money from the point of TSO and generator operators and the loss of a vital facility in the sense of citizens.

6. References

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