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Investigating a Ranking of Loads in Avoiding Potential Power System Outages

***Abstract**. In this work, we consider the impact or sensitivity of loads to likely power system contingencies that would require the adoption of demand management programs and we establish a frame work for determining the most critical loads and ranking them. Moreover we develop a novel weighted average approach that can be modified to specific power system needs and determine the most effective load for a number of likely contingencies. The methodologies developed in this work are tested on a wide range of sample power system test cases with successful results*

***Streszczenie.** W artykule przedstawiono wyniki prac dotyczących badania wpływu oraz wrażliwości odbiorników na możliwe awarie w systemie energetyczny, ingerujące w zarządzanie dystrybucją mocy. Opracowany został system segregacji i oceny najbardziej wrażliwych odbiorników. (**Opracowanie rankingu odbiorników pod względem odporności na potencjalne problemy w systemie energetycznym**)*

Keywords: Power System Outages, Demand Management Programs, Electric Loads, Sensitivity Analysis.
Słowa kluczowe: Analiza wrażliwości, zarządzanie poborem energii w sieci, blackout, awaria sieci, odbiorniki elektryczne.

Introduction

Demand Side Management (DSM) aims to control the consumer's consumption of electrical energy while at the same time preserving general power system health [1],[2]. Of crucial importance in DSM programs is determining the customers (or loads) that have the greatest effect on the power network, as offering demand management programs to these select customer(s) at critical times can often prevent power system collapse. In this paper we show via an analysis of the various interacting components of a power system, that it is possible for utilities to measure the impact of loads on forced outages in a power system. Furthermore we present a designed methodology that ranks the loads and their impact on the system for a given number of contingencies and determines the load with the most impact. Contingencies like generator outage, voltage collapse, transmission line outages, etc. and useful power system index like Power Transfer Distribution Factor (PTDF) will be used in our analysis. This work is motivated by the authors' research on power system demand management contract formulations [3]-[5] where it is crucial for customers to curtail their loads. Knowing important customers will in the final analysis make for optimality in contract formulation. This paper is organized as follows: in the next section we present a method for determining the most sensitive loads to line outages, followed by a section describing a method of computing the sensitivity of loading margin to voltage collapse with respect to each load. The next section describes a method for measuring the impact of loads on generator outages. The last section presents a novel weighted average approach to computing the value of power interruptibility for a number of power system contingencies after which the paper is concluded.

Impact of Loads on Line OutagesFormatting of the text

It is possible to determine the impact of loads on line flows and outages. To determine this it would be necessary to review Power Transfer Distribution Factors (PTDF) [6],[9]. PTDF for any power system can be represented by a matrix of size n_l x n_b where n_l is the number of lines and n_b is the number of buses. If D is a PTDF matrix, then d_{ij} represents the change in the real power in branch i given a unit increase in the power injected at bus j, with the assumption that the additional unit of power is extracted according to some specified "slack" distribution. Since loads are negative power injections it is possible to use the PTDF matrix to determine impact of the loads on line outages. This analysis is performed on the 6 bus Wood and Wollenberg example system (shown in Fig.1) with 3 generators (buses 1, 2, 3) and 3 loads (buses 4, 5, 6) using MATPOWER [7] and bus 1 is the slack bus or reference bus. Table 1 presents the obtained results.

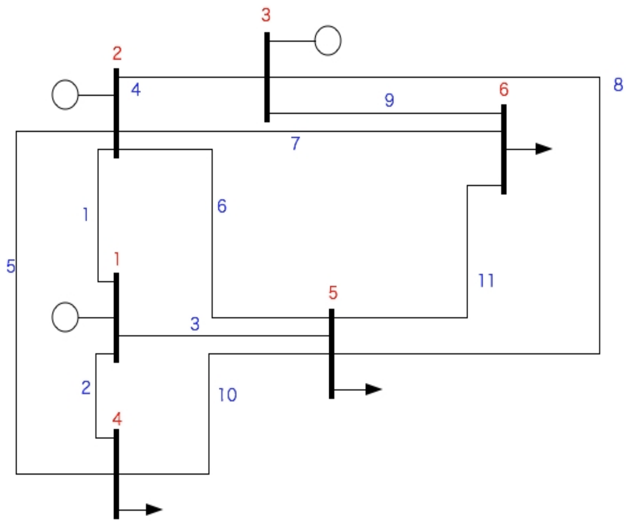

Fig.1. The 6 bus Wood and Wollenberg example system

In Table 1, in each row we highlight in bold the load buses that affect the line the most. They are simply the largest numbers. So for the line from bus 5 to bus 6, the load at bus 6 affects the line the most i.e. **0.2467** is the largest number on the row. Note that the bus 1 column is 0, because we assumed a single slack for PTDF calculations. A careful analysis of Table 1 shows that the load at bus 6 affects the most lines (5 lines); therefore for a power system susceptible to line outages, the customer at bus 6 is a prime candidate for demand management.

Sensitivity of the Loading Margin to Voltage Collapse with Respect to Each Load

This analysis relies heavily on the derivations in [8]. In [8] the authors present a method for calculating the sensitivity of the loading margin of a system with respect to arbitrary parameters. In this work we assume loads are the parameters and we seek to compute the sensitivity of the loading margin with respect to each load.

(1) $$g(\nu,\gamma,\rho)=0$$

Table 1. PTDF's for the 6 Bus Wood and Wollenberg example system, showing the buses and hence loads with the highest effect on line outages. Buses 4, 5, 6 are the load buses

From Bus	To Bus	Bus1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
1	2	0	0.4706	0.4026	0.3149	0.3217	**0.4064**
1	4	0	0.3149	0.2949	**0.5044**	0.2711	0.296
1	5	0	0.2145	0.3026	0.1807	**0.4072**	0.2976
2	3	0	-0.0544	0.3416	-0.016	0.1057	**0.1907**
2	4	0	-0.3115	-0.2154	**0.379**	-0.1013	-0.2208
2	5	0	-0.0993	0.0342	-0.0292	**0.1927**	0.0266
2	6	0	-0.0642	0.2422	-0.0189	0.1246	**0.41**
3	5	0	-0.0622	-0.289	-0.0183	**0.1207**	-0.1526
3	6	0	0.0077	-0.3695	0.0023	-0.015	**0.3433**
4	5	0	0.0034	0.0795	-0.1166	**0.1698**	0.0752
5	6	0	0.0565	0.1273	0.0166	-0.1096	**0.2467**

where v is the vector of state variables, γ is vector of real and reactive load powers and ρ is vector of loads. The point of collapse method can be used to obtain the left eigenvector when a pattern of load increase is specified with a unit vector *k.*

The sensitivity of loading margin to a change in any load is therefore computed as:

$$\frac{\Delta L}{\Delta \rho} = L_{\rho} = \frac{-\omega g_{\rho}}{\omega g_{\gamma} k}$$

(2)

We can go on and relate changes in individual load to change in security margin:

(3) $$\Delta L = L_{\rho 1}\Delta\rho_1 + L_{\rho 2}\Delta\rho_2 + ... + L_{pm}\Delta p_m$$

where *m* is the number of loads of interest. We observe that the load with highest sensitivity would increase the loading margin the most.

It should be noted that other kinds of sensitivities can be computed as well.

Table 2. Sensitivity of the Loading Margin to Voltage Collapse With Respect to Each

Load Bus	Sensitivity (MW/MW)
2	-0.03
4	-0.89
5	-0.12
6	-1.48
7	**-1.73**
8	**-1.73**
Loading Margin = 36.18 MW	

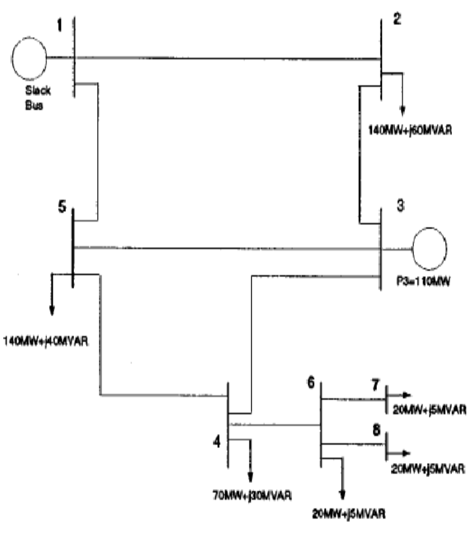

Fig.2. The 8 bus example system

This analysis is presented on the 8 bus system with 2 generators and 6 loads shown in Fig.2. Of concern is the loading margin to voltage collapse. If the load is increased equally on each load bus and only the slack generator picks up the extra load, the sensitivity of the loading margin to voltage collapse with respect to a change in each load is shown in Table 2. In this example the most valuable loads are 7 and 8. They have the highest sensitivity.

Impact of Loads on Generator Outages

It is possible to calculate the impact of loads on generator outages. Locational Marginal Prices (LMP) or Locational Based Marginal Price (LMBP) are defined in [9] as the cheapest way one can deliver one MW of electricity to an electric power system node from the available system generators while respecting all the system limits and constraints in effect. LMP's are usually calculated as a by-product of Optimal Power Flow (OPF) [10], though they can also be calculated via soft computing methods [11]. Thus LMP provide a veritable means for calculating the most sensitive loads to generator outage. After LMP is determined normally, take out a generator and re calculate LMP. The load that has the highest LMP increase (Δ LMP) is the most sensitive load. The analysis is performed on the IEEE 14 bus system shown in Fig. 3 and Table 3 presents the results where

(4) $$\Delta \text{ LMP} = \text{LMP}_{normal\ operation} - \text{LMP}_{\text{generator outage}}$$

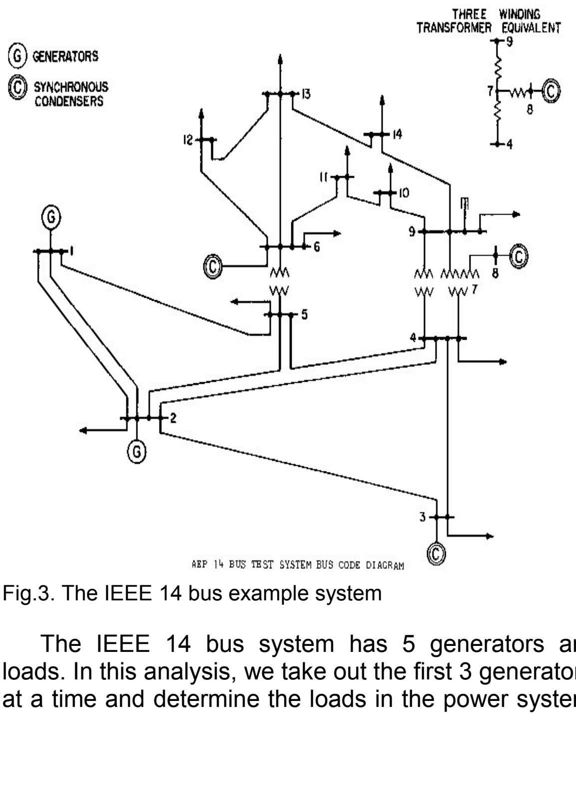

Fig.3. The IEEE 14 bus example system

The IEEE 14 bus system has 5 generators and 11 loads. In this analysis, we take out the first 3 generators one at a time and determine the loads in the power system that affect the generators the most. Looking at Table 3, when generator 1 goes offline, the ∆ LMP is greatest at load bus 2, followed by load bus 12, therefore these loads have the most effect on generator 1. Again when generator 2 goes offline, the ∆ LMP is greatest at load bus 2, followed by load bus 14, therefore these loads have the most effect on generator 2. And finally, when generator 3 goes offline, the ∆ LMP is greatest at load bus 3, followed by load bus 2, therefore these loads have the most effect on generator 3. This analysis can be extended to other generators in the power system. For a power system that is susceptible to generator outages, and in need of demand management programs, knowledge of customers that impact the generator the most is required.

Table 3. Sensitivity of the Loads to Generator Outages

	Normal	Gen 1 Out	Gen 2 Out	Gen 3 Out
Loads	LMP ($)	∆ LMP	∆ LMP	∆ LMP
Bus 2	38.3596	**2.8644**	**0.6307**	0.5156
Bus 3	40.5749	1.0537	0.2393	**1.3436**
Bus 4	40.1902	1.293	0.2862	0.3869
Bus 5	39.6608	1.6822	0.3353	0.3603
Bus 6	39.7337	1.4196	0.3607	0.3972
Bus 9	40.1715	1.4044	0.2809	0.3636
Bus 10	40.1699	1.3931	0.2757	0.3575
Bus 11	40.1662	1.4772	0.2833	0.3595
Bus 12	40.3178	1.4841	0.2968	0.3677
Bus 13	40.1554	1.4638	0.3277	0.382
Bus 14	40.3791	1.4378	0.3633	0.4035

Weighted Average Approach to Computing Value of Power Interruptibility

In a power system, a number of contingencies are always very likely and cause a lot of damage to power systems [12]. Since demand management programs aim to sustain power system reliability, there is the need for a method of estimating the various possible contingencies and determining the customers (loads) that should be offered demand management programs. The key to this is in the calculation of the power interruptibility value (λ). Existing optimal power flow routines can be used to calculate this value for each location in the system. However, the effect of the most probable contingencies has to be incorporated into the calculation of λ. There exist some critical locations which can pose a problem to the whole system. These locations need to have a high power interruptibility value in order to emphasize their importance and help in signing up the respective customer. Careful calculation of the λ values for each location will help the contracts address more potential utility problems. After calculating the λ values using optimal power flow routines for each contingency [10], [11], the proposed suggestion is to use a weighted average approach to determine the value of interruptible power at each location. Suppose that the utility assigns a weight w_i on each contingency they anticipate, and they compute the λ value for each contingency for that location. Assuming they anticipate z different contingencies, the weighted average of λ at the kth customer location will be given by:

$$\lambda_{k,avg} = \frac{\sum_{i=1}^{z} w_i \lambda_i}{\sum_{i=1}^{z} w_i} \qquad (5)$$

This weighted average approach is applied to the IEEE 9 bus system (Fig.4) which has 3 generators, 3 loads and 9 lines. Due to space constraints we limit the number of contingencies to individual generator outages and individual line outages making a total of 12 contingencies (9+3). We assume generator outages are more likely and devastating than line outages (This is power system dependent, some power systems are more susceptible to line outages). We design 6 weights: (1,2,3,4,5,6) with 6 being the weight in the event of the highest generator outage, 5 the second highest generator outage and 4 the least generator outage. The 9 lines are ranked based on their "active power flow". Thus the top three lines have a weight of 3, the next three lines a weight of 2 and the last three lines a weight of 1 in case of a line outage We then obtain λ for each of these contingencies and used equation 5 to obtain λ_{avg} for each bus.

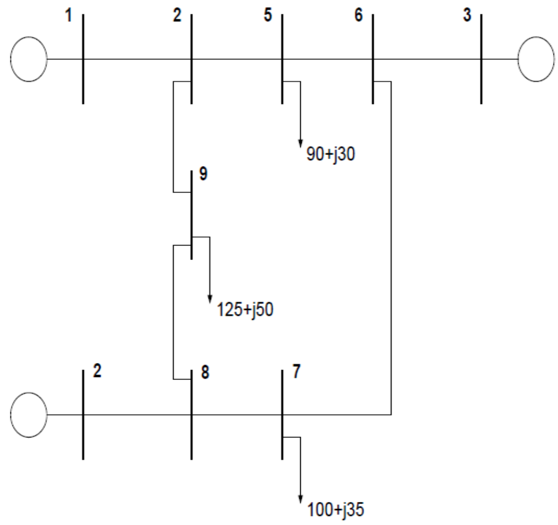

Fig.4. The 9 bus example system

Table 4. Weighted Average Approach to Computing λ_{avg} and ranking loads based on likely contingencies

Bus No	λ	λ_1		λ_{12}	λ_{avg}	*Bus Rank*
1	24.7557	0	...	33.83	32.591	7
2	24.0345	29.88	...	33.09	25.172	8
3	24.0759	39.95	...	33.9	14.669	9
4	24.7559	97.06	...	33.83	98.089	6
5	24.9985	99.64	...	34.46	127.213	2
6	24.0759	47.58	...	33.9	119.336	4
7	24.2539	56.08	...	33.72	130.113	1
8	24.0345	57.99	...	33.09	102.624	5
9	24.9985	93.73	...	34.26	126.250	3

The loads are now ranked (column 7, Table4) on the basis of their λ_{avg} with the highest λ_{avg} the most influential load/customer for demand management. Now there are only 3 load buses in the IEEE 9 bus system (Bus 5, 7, 9) and based on our yardstick λ_{avg} they are ranked 2nd, 1st and 3rd respectively, thereby validating our methodology. It can be shown that curtailing the loads can reduce the λ_{avg} value [5].

Conclusions

Demand management programs that assume that all loads should be treated equally suffer from non-optimality. There is the need for a methodology of determining the loads with the most impact on a power system for a number of likely contingencies. Therefore in this work, we detailed various methodologies for determining the high impact loads in a power system. We determined loads that had the highest impact on line outages, loads that had the highest impact on generator outages and utilized a method for determining the sensitivity analysis of the loading margin to voltage collapse with respect to each load. Finally a novel weighted average approach for determining the most important loads to two likely contingencies (generator and line outages) was presented and verified. All the methods were tested on a wide number of power system test cases and all the obtained results show the robustness and accuracy of our methodologiesis

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