Determining Appropriate Buses and Networks for Applying Demand Side Management Programs by Structural Analysis of EENS

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Abstract

The main goal of this paper is to structurally analyze impact of DSM programs on reliability indices. A new approach is presented to structurally decompose reliability index Expected Energy Not Supplied (EENS) by using Monte Carlo simulation. EENS is decomposed into two terms. The first term indicates EENS which is caused by generation contingencies. The second term indicates EENS which is caused by transmission and generation contingencies. The proposed approach can be used to indicate appropriate buses for applying DSM. Furthermore, networks are studied at two levels; HLI and HLII. Studies show that in some networks reliability indices are affected mostly at the HLI level. While in some other networks, reliability indices are influenced mostly at the HLII level. It means that in these networks, reliability indices are affected by transmission contingencies. Then, it is shown that the implementation of load shifting is effective in some networks and buses. These are the ones which their EENS is more influenced by generation contingencies. However; it is not effective in the ones which their EENS is more influenced by transmission contingencies. The simulation results on the IEEE-RTS and Khorasan network show the efficiency of the proposed approach.

Key words: Expected Energy Not Supplied (EENS), Demand Side Management (DSM), Monte Carlo Simulation, Reliability

1. Introduction

1.1. Motivation

Demand Side Management (DSM) is an efficient tool to reduce peak demand. Utilities can use DSM to delay the construction of new generation resources. In fact, by reducing peak demand, DSM will have different effects such as: reducing the number of outages, improving system reliability, reducing energy costs and decreasing the harmful activities for the environment [1]-[2]. In general, DSM plays a significant role in operation and planning of generation, distribution and transmission systems. DSM applied to power system has a wide range of economic, environmental and reliability advantages [3]-[4]. Therefore, various studies have been carried out on the impact of DSM programs on generation, distribution and transmission systems [5]-[6]. Moreover, it is important to study the implication of DSM programs in power system reliability [7].

1.2. Literature Review

In order to represent the effect of DSM programs on power system, reliability indices are studied [8]-[9]. System reliability indices (LOLE & LOEE) increase significantly with increasing load forecast uncertainty. The application of demand side management tends to counteract the effects of load forecast uncertainty and therefore, reduce the inherent increase in the system reliability indices due to the load forecast uncertainty [9]. Reference [7] shows that the benefits of DSM on different load sectors will be varied. It can be seen that the DSM measures affect system loads and reliability indices differently when applying DSM on system load, bus loads, and all load sectors. It is easier to apply DSM directly to system load or bus loads in generating capacity adequacy assessment compared to applying DSM on individual load sectors .It is, however, more accurate to apply DSM to the individual load sectors [7]. References [2], [10] and [6]show the effect of DSM on system reliability. These studies are mainly based on the total load profile that does not include the load sectors. In reference [2] an approach is presented to estimate the impacts of DSM programs on composite system reliability in Mont Carlo simulation approach. The results show that DSM programs have obvious contribution to composite system reliability improvement. Reference [10] illustrates how the optimal planning reserve margin can vary with the introduction of DSM. The DSM programs illustrated in [6] can improve system reliability by modifying the load model. The system and load point indices decrease when effective DSM programs are applied and the system becomes more reliable and secure. References [11] and [12] show the impact of DSM programs on the power system reliability indices, when they are applied to the residential sector. However, despite the presented studies on DSM, no structurally analysis for evaluating the impact of DSM programs on reliability indices can be found in the literature.

1.3. Approach and Contribution

The main goal of this paper is to structurally analyze the impact of DSM programs on the reliability indices of the power system. As shown in Fig. 1, In order to achieve this goal, a novel three step modeling is presented. At the first step, the reliability indices of networks are calculated before applying DSM programs at HLI and HLII levels. Studies show that in some networks, the reliability indices are influenced mostly at the HLI level. While in some other networks, the reliability indices are affected mainly at the HLII level. It means that in these networks, the reliability indices are influenced by transmission and generation contingencies.

At the second step, a new approach is presented to structurally decompose the reliability index Expected Energy Not Supplied (EENS) by using Monte Carlo simulation. In Monte Carlo simulation, states are divided into two parts. Then EENS is decomposed into two terms. The first term indicates the amount of EENS which is caused by the generation contingencies. The second term indicates the amount of EENS which is affected by transmission and generation contingencies. Therefore, the proposed approach can be used to structurally analyze the reliability index of each bus and determine how much EENS of each bus is caused by the generation contingencies or transmission and generation contingencies.

At the third step, first due to the concept of Load Shifting (LS), which is used in this paper as one of the DSM programs and its impact on Load Duration Curve (LDC), it is shown that the application of load shifting is effective in the reliability indices of some networks and buses. These are the ones which their reliability index EENS is more influenced by the generation contingencies. However; it is not effective in the ones which their EENS is more influenced by transmission and generation contingencies. Therefore, the proposed approach can be used to indicate the appropriate buses and networks for applying DSM programs. Then, load shifting program is applied to the buses of IEEE 24-bus Reliability Test System (IEEE-RTS) and Khorasan 400 KV network. The simulation results on these networks show the efficiency of the proposed approach to indicate the appropriate buses and networks for applying DSM programs.

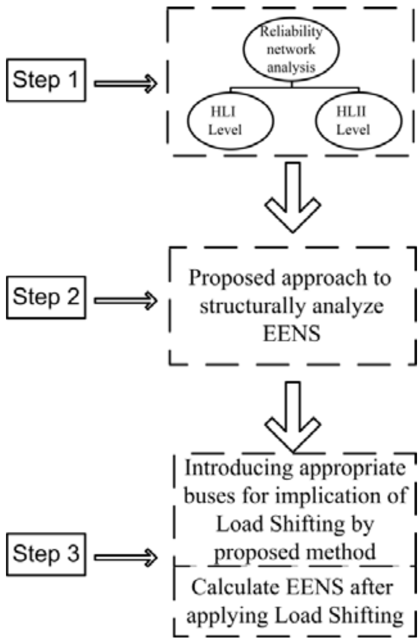

Fig. 1. The proposed model

1.4. Paper Organization

The rest of this paper is organized as follows: Section 2 includes problem formulation .Section 3 introduces the proposed EENS decomposition approach and the new Monte Carlo flowchart which is presented to calculate reliability indices. The impact of load shifting on reliability index EENS is evaluated from two points of view in section 4. Section 5 includes the simulation results of IEEE-RTS and Khorasan 400kv network after and before applying DSM programs. Finally, the paper is summarized and concluded in section 6.

2. Problem Formulation

2.1. Demand Side Management Programs and Their Impact on Load Duration Curve

Utilities are one of the main executers of DSM programs. The consumers can benefit from these programs; they also can manage and implement these programs. The sectors with independent activities such as private buildings and industrial constructions are really interested in DSM programs, in order to reduce their energy consumption and energy costs by implementing them. Moreover, they may help utilities in providing energy more efficiently.

DSM, in general, refers to any program adopted by utilities that changes the utilities' Load Duration Curve. These changes include: Peak Clipping, Valley Filling, Load Shifting, Strategic Load Growth, Strategic Conservation and Flexible Load Shape, and each of these changes will have many benefits for the utilities and the consumers [13].

In this paper, equation (1) is used to study the effect of load shifting program on LDC ([4], [6], [7], [9] and [10]).This equation is for 24 hours load and it studies the changes of load curve during 24 hours. P is the preferred peak demand of the system that results from the implementation of load shifting. Any load above P is reduced and shifted to off-peak hours. The amount of energy shifted to off-peak hours depends on the value of α in equation (1). The variable p is the first time during the day when the original load is greater than the P (L (t)>P). The variable q is the last time during the day when the original load is greater than P. The starting time for off-peak recovery of energy is presented by t_1 and the ending time for off-peak recovery of energy is presented by t_2. The difference between t_1 and t_2 defined as h is the amount of time which energy will be recovered. The range for α is $0 \leq \alpha \leq 1$ and depends on the amount of recovered energy required during off-peak hours.

$$\hat{L}(t) = L(t) - \left\{ \left(L(t) - P \right) \Omega(L(t)) \right\} + \alpha \left\{ \frac{\sum_{T=p}^{q} \left\{ (L(T) - P) \Omega(L(t)) \right\}}{h} \right\} \lambda(t_1, t_2)(t)$$

$$\begin{aligned} &\Omega(L(t)) = 1 \quad for \quad L(t) > P \\ &\Omega(L(t)) = 0 \quad for \quad L(t) \le P \\ &\lambda(t_1, t_2)(t) = 1 \quad for \quad t_1 \le t \le t_2 \\ &\lambda(t_1, t_2)(t) = 0 \quad for \quad other \quad values \quad of \quad t \end{aligned} \tag{1}$$

In this paper, on-peak and off-peak hours are considered as the preferred peak demand of the system and the valley load values, respectively. The energy reduced during a day shifted to the off-peak hours. Therefore, daily load curve and LDC of each bus and network will be modified.

2-2 **Power System Reliability Assessment**

Many indices and methods to assess the reliability of power system have been already studied. Monte Carlo simulation is usually used to assess power system reliability at HLII level. Considering generation and transmission contingencies, different configuration of the system can be occurred in Monte Carlo simulation. In this paper, in order to evaluate the reliability of power system at HLII level, the reliability index EENS is calculated for all the buses. This index shows the expected energy that is not supplied by the power system in a specified time period, usually manually [15].

To evaluate EENS corresponding to each bus, it is necessary to determine the maximum amount of load that can be supplied at ith configuration of the network P_n^{i*}. Considering a specific configuration of the network, the following optimization problem should be solved to compute P_n^{i*}. The optimization problem includes; power flow limits, power balance at each bus, generation and transmission constraints.

$$
\begin{aligned}
&Min \quad -\sum_{n=1}^{N} IEAR \times P_n^i \\
&such \quad that: \\
&\sum P_g^i - P_n^i - \sum f_l^i = 0 \quad for \quad n = 1,\dots,N \\
&f_l^i - \gamma_l(\theta_i - \theta_j) = 0 \quad for \quad l = 1,\dots,L \\
&\left| f_l^i \right| \le Max(f_l^i) \\
&0 \le P_g^i \quad for \quad g = 1,\dots,G
\end{aligned}
\qquad (2)
$$

By solving the above linear programming problem, maximum value of P_n^i can be computed, considering the Interrupted Energy Assessment Rate (IEAR). The first constraint is power balance at each bus. The second constraint demonstrates DC load flow. The third, the fourth and the fifth constraints are maximum transmission line capacities, maximum generation of generators and maximum bus load, respectively. In this equation N is the number of network buses, G is the number of generators and L is the number of lines.

3- Structural analysis of EENS

Fig. 3 shows the new proposed Monte Carlo simulation flowchart. When a new configuration is recognized in Monte Carlo simulation, the number of islands in the network is determined and a slack bus to each island is determined. The energy not supplied will be calculated in each configuration of each bus with respect to these P_n^{i*}. As shown in Fig. 4, the amount of energy between P_n^{i*} and P_{MD} is not supplied by the specific bus n with maximum power demand P_{MD} ,which is expected to supply by the system. The results of each configuration will be saved and if that configuration occurs again in Mont Carlo simulation, the previous results will be used. One of the advantages of presented flowchart is its high speed.

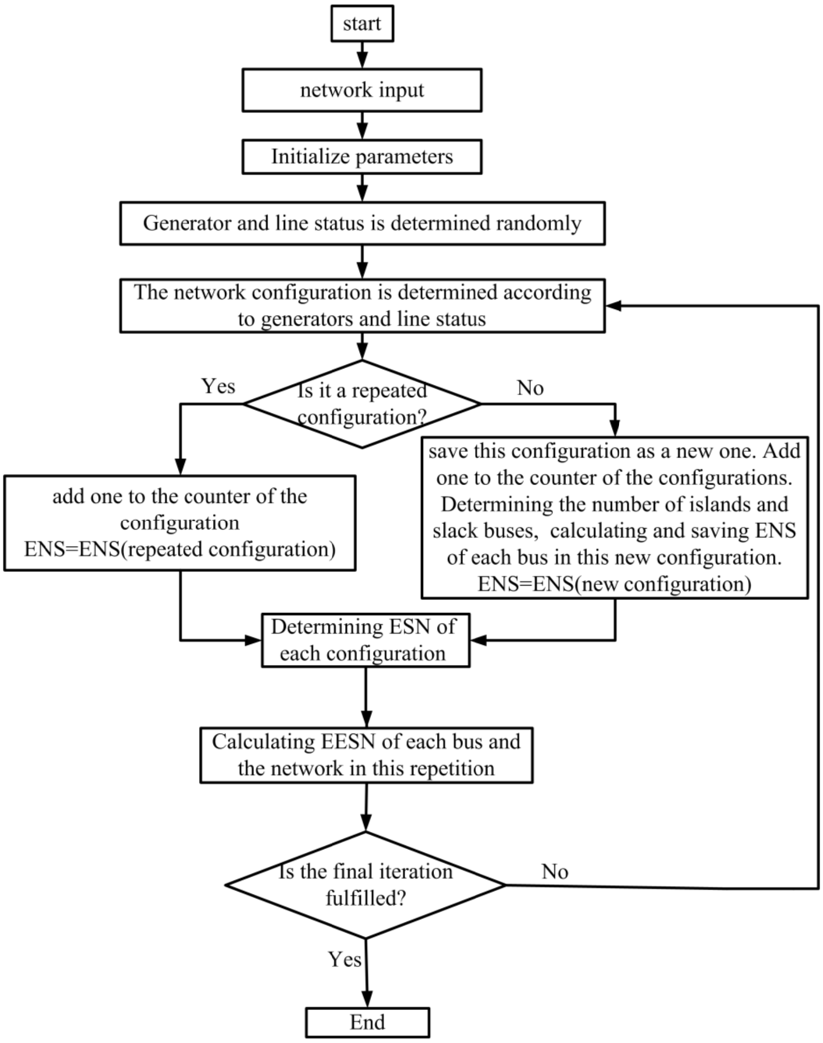

Fig. 3. New flowchart to calculate reliability indices

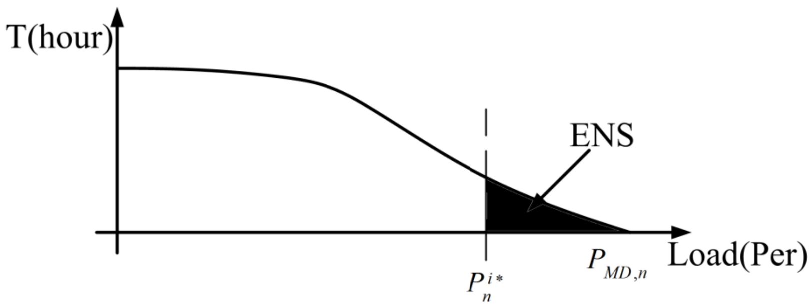

Fig. 4. Calculating ENS corresponding to bus n at configuration i

The main advantage of proposed flowchart is that the number of states and the number of repetition of each state are determined. Therefore, the probability of each state and the load flow results of each state are calculated at the end of the program.

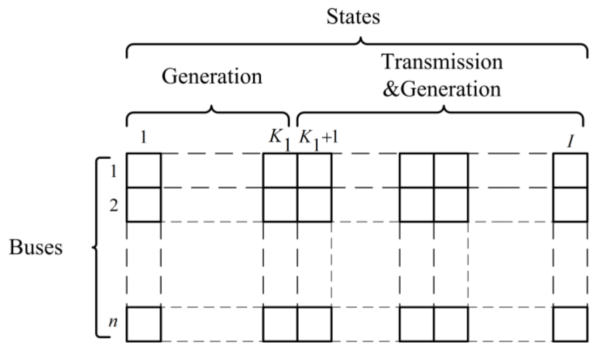

Fig. 5. States divided into two parts in Monte Carlo simulation

As shown in Fig. 5, the states in Monte Carlo simulation can be divided into two parts. The horizontal and vertical axes are corresponding to the states and the network buses in Monte Carlo simulation, respectively. I and n are the total number of states and the total number of buses, respectively. The first part, which contains *1* to K_1 states in Fig. 5, only illustrates the states caused by generation contingencies. It means only the states, in which all lines are available, are considered. As a result, EENS is caused only by generation contingencies in these states. The second part, which is contains K_1 *+1* to I states, illustrates the states caused by generation and transmission contingencies simultaneously. As a result, EENS is caused by generation and transmission contingencies in these states

Lemma1 expresses the decomposition of EENS into two terms.

Lemma1. For the specific network topology and the specific bus n, $EENS_n$ is decomposed as follows:

$$EENS_n = EENS_{G,n} + EENS_{T,n} \quad (3)$$

in which, $EENS_{G,n}$ indicates $EENS_n$ caused by generation contingencies and $EENS_{T,n}$ indicates $EENS_n$ caused by transmission contingencies.

Proof. To calculate $EENS_n$, the probability of states is determined in Monte Carlo simulation. EENS of each state at each bus is indicated as $EENS_{n,i}$. $EENS_{n,i}$ is calculated by multiplying the probability of state i to the Energy Not Supplied of that state at each bus. Moreover, $EENS_n$ is the summation of $EENS_{n,i}$. Therefore;

$$EENS_n = \sum_{i=1}^{I} EENS_{n,i} = \sum_{i=1}^{I} \left(\Pr_i \times ENS_{n,i} \right) \quad (4)$$

Where Pr_i is the probability of state i and $ENS_{n,i}$ is the Energy Not Supplied of state i at bus n.

As shown in Fig. 5, states can be divided into two parts. Therefore, $EENS_n$ can be expressed as:

$$EENS_n = \sum_{i=1}^{K_1} \left(\Pr_i \times ENS_{n,i} \right) + \sum_{K_1+1}^{I} \left(\Pr_i \times ENS_{n,i} \right) \quad (5)$$

where

$$\begin{cases} EENS_{G,n} = \sum_{i=1}^{K_1} \left(\Pr_i \times ENS_{n,i} \right) \\ EENS_{T,n} = \sum_{K_1+1}^{I} \left(\Pr_i \times ENS_{n,i} \right) \end{cases}$$

The first summation indicates the amount of EENS influenced by generation contingencies. The second summation indicates the amount of EENS influenced by generation and transmission contingencies simultaneously. Therefore, $EENS_n$ is decomposed into two terms and Lemma1 is proved. ڤ

4- Impact of DSM on Network Reliability

In this section, the impact of load shifting program on the reliability index EENS is evaluated from two points of view. First, the impact of load shifting on each bus is examined and appropriate buses are presented to apply this program. Then, the impacts of load shifting on the networks are examined and appropriate network is presented to apply this program.

4-1 Impact of DSM on Bus EENS

In this paper, the impact of DSM programs on the LDC will be studied. As shown in Fig. 6, the DSM programs reduce and shift the amount of energy during peak hours to off-peak hours.

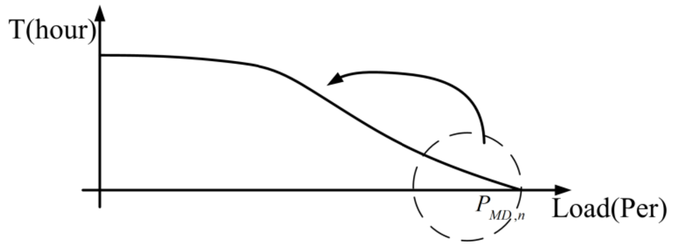

Fig. 6. LDC changes due to applying DSM programs

It is expected that the reliability index will not be improved on the buses, in which their $EENS_n$ is caused by transmission contingencies. However, in these buses, energy from peak hours is shifted to off-peak hours by the application of load shifting, but energy not supplied is not decreased. It means $ENS_{n,i}$ is not changed by applying load shifting, as shown in Fig. 7. Therefore, $EENS_n$ will not be improved by the application of DSM programs. Also, it is expected that the reliability index will be improved on the buses, in which their $EENS_n$ is caused by generation contingencies. In these buses, energy from peak hours is moved to off-peak hours by the implication of load shifting and energy not supplied is decreased, as shown in Fig. 8. Therefore, $EENS_n$ will be improved by applying of DSM programs.

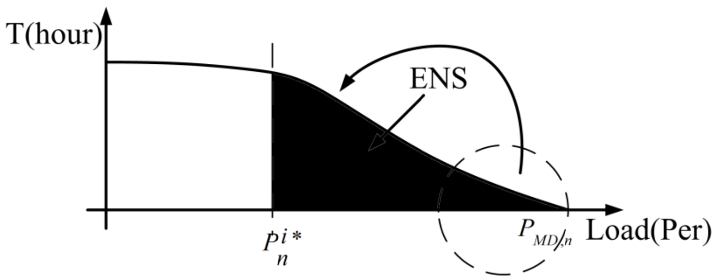

Fig. 7. ENS caused by transmission contingencies

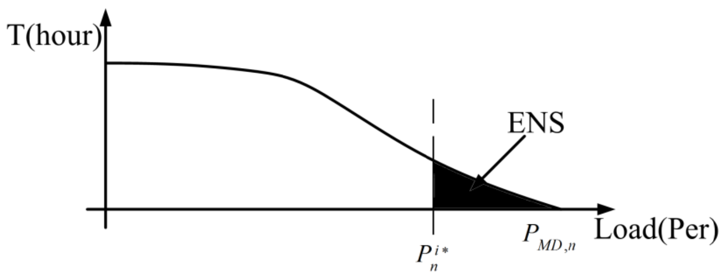

Fig 8. ENS caused by generation contingencies

4-2 Impact of DSM on Network EENS

Studying the impact of DSM programs on reliability indices of network is an effective way to define the appropriate network for applying DSM programs.

In [16], EENS of a transmission system is expressed as the difference between the HLI and HLII reliability indices, as shown in equation (6):

$$EENS_{Trans} = EENS_{HLII} - EENS_{HLI} \qquad (6)$$

Once $EENS_{HLII}$ is much greater than $EENS_{HLI}$, the network has been affected by transmission contingencies. Therefore, it is expected that network reliability will not be improved by applying DSM programs. On the other hand, once $EENS_{HLII}$ and $EENS_{HLI}$ are close to each other, the network has been affected by generation contingencies. Therefore, network reliability is improved by applying DSM programs.

In the rest of this paper, the impact of applying DSM programs on the IEEE-RTS and Khorasan 400 KV network is studied and appropriate network buses are determined for applying DSM programs.

5. Case Studies: IEEE-RTS Network and 400 KV Khorasan Network

In this section, the impact of applying DSM programs on the IEEE-RTS and Khorasan 400KV network will be discussed.

According to Fig. 9.a, in Khorasan 400 KV network, total load is 2229 MW and generation capacity is 3752 MW in 14 buses. The IEEE-RTS network has a total generation capacity of 3450 MW in 24 buses and has a total load of 2850 MW [17], as shown in Fig. 9.b. These two networks have different LDC and they will be changed by applying load shifting.

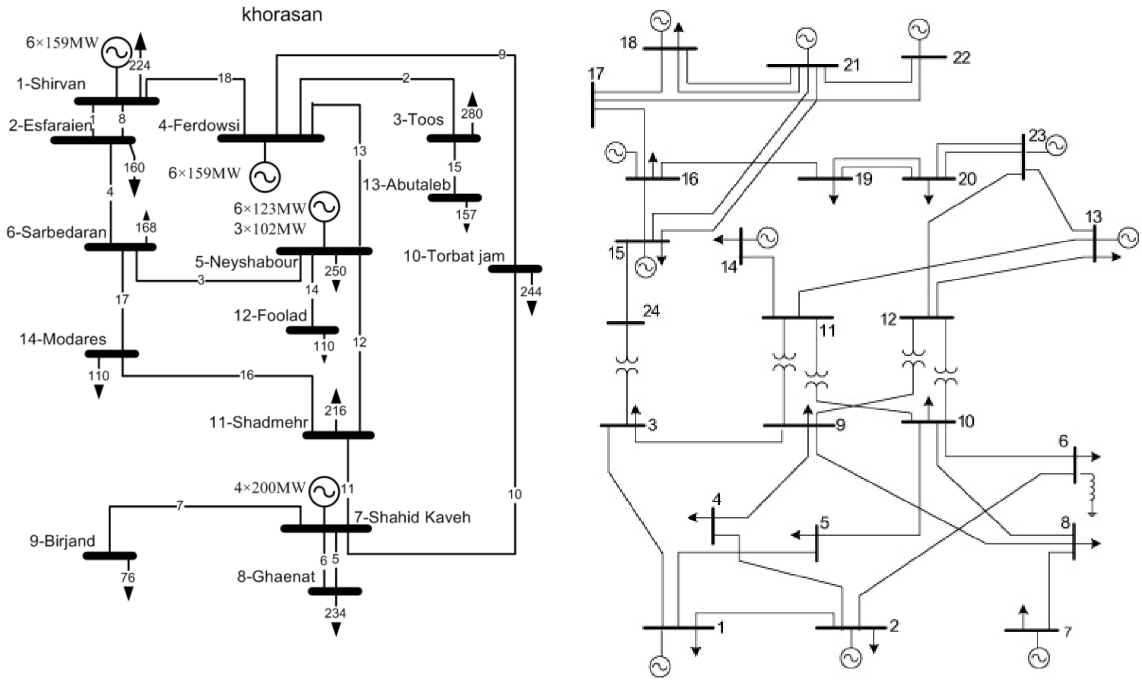

Fig. 9. a) Khorasan 400KV network b) IEEE Reliability Test System

5-1 Case Study 1: Studying the Impact of DSM Programs on Both HLI and HLII Levels

In this section, first EENS values are calculated for the IEEE-RTS and Khorasan 400 KV network before applying DSM programs. EENS values at both HLI and HLII levels are shown in Table 1.

Table I. EENS of Khorasan and IEEE-RTS networks before applying DSM

	$EENS_{HLII}$ (MWh/yr)	$EENS_{HLI}$ (MWh/yr)	$EENS_{trans}$
Khorasan network	2067.6	almost 0	2067.6
IEEE-RTS	1853.26	1836.5	16.76

According to equation (6), $EENS_{trans}$ for the IEEE-RTS and Khorasan network are 16.76 and 2067.6 MWh/yr, respectively, as shown in Table I. It can be seen that Khorasan network has been affected by transmission contingencies more and IEEE-RTS has been affected by generation contingencies more.

Now, load shifting is implemented on these two networks at HLII. The results of applying load shifting at peak 0.9 p.u. and α=1, which means total reduced energy in peak hours has moved to non-peak hours, are shown in Table II.

As shown in Table II, total EENS of Khorasan network is improved only 8.1 MWh/yr which means 0.4% improvement on total EENS but total EENS of the IEEE-RTS is improved 568.95 MWh/yr which means about 30% improvement on total EENS. According to Tables I and II, it can be seen that load shifting has significant effect on the network, such as the IEEE-RTS, that has been affected by generation contingencies and it has slight effect on the network, such as Khorasan network, that has been affected by transmission contingencies.

Table II. EENS of the Khorasan network and IEEE-RTS after and before applying LS100

	before applying LS100	after applying LS100	Difference
Khorasan network	2067.6	2059.5	8.1
IEEE-RTS	1853.26	1284.31	568.95

5-2 Case Study 2: Studying the Effect of DSM Programs on Network Buses

In this section the impact of load shifting on each network bus of the IEEE-RTS and Khorasan 400 KV network is studied. Tables III and IV show $EENS_n$ of Khorasan 400 KV network and IEEE-RTS before applying load shifting.

Table III. EENS of Khorasan buses before applying load shifting

Bus	$EENS_n$	$EENST_{T,n}$	$EENSG_{G,n} \times 10^{-7}$
3	22.9	22.9	3.5
9	1153.23	1153.23	5.6
10	38.2	38.2	3.55
12	189	189	3.91
13	660.04	660.04	3.55
total	2067.6	2067.6	20.11

$EENSG_{G,n}$ and $EENST_{T,n}$ can be calculated for each bus of Khorasan network and IEEE-RTS by equation (3). As shown in Tables III and IV, it can be seen that $EENSG_{G,n}$ is much more than $EENST_{T,n}$ in IEEE-RTS. Therefore, these buses are affected more by generation contingencies. But $EENST_{T,n}$ is much more than $EENSG_{G,n}$ in Khorasan network. Therefore, these buses are affected more by transmission and generation contingencies.

Considering the points given, it is expected that the $EENS_n$ of Khorasan network will not be improved, but the $EENS_n$ of IEEE-RTS will be improved after applying DSM programs. The results of applying LS100 are shown in Tables V and VI. The percent improvement of $EENS_n$, $EENS_{T,n}$ and $EENS_{G,n}$ are expressed in these tables. As shown in Table V, the $EENS_n$ of Khorasan has been improved slightly and as shown in Table VI, the $EENS_n$ of IEEE-RTS has been improved a lot after applying DSM programs. Therefore, the buses, in which their $EENS_{G,n}$ are much more than $EENS_{T,n}$, are appropriate to apply DSM programs. On the other hand, applying DSM programs on the buses, in which their $EENS_{G,n}$ are much less than $EENS_{T,n}$, are not effective to improve $EENS_n$.

Table IV. EENS of the IEEE-RTS buses before applying load shifting

Bus	$EENS_n$	$EENS_{T,n}$	$EENS_{G,n}$
9	374.54	10.32	364.22
14	4.2	0.36	3.84
15	103.89	2.94	100.95
19	1370.63	37.31	1333.32
Total	1853.26	50.93	1802.33

Table V. EENS of the Khorasan network buses after applying load shifting

	after applying DSM programs			Percent improvement (%)		
Bus	$EENS_n$	$EENS_{T,n}$	$EENS_{G,n}\times10^{-7}$	$EENS_n$	$EENS_{G,n}$	$EENS_{T,n}$
3	22.9	22.9	1.69	0	almost 0	0
9	1153	1153	2.06	0		1
10	37.6	37.6	1.65	1.5		1
12	188	188	1.53	0.5		1
13	658	658	1.68	0.3		1
Total	2059.5	2059.5	8.61	0.4		1

Table VI. EENS of the IEEE-RTS buses after applying load shifting

	After applying DSM programs			Percent improvement (%)		
Bus	$EENS_n$	$EENS_{G,n}$	$EENS_{T,n}$	$EENS_n$	$EENS_{T,n}$	$EENS_{G,n}$
9	253.82	245.78	8.04	32.2	1.9	98.1
14	2.32	2.1	0.22	44.7	7.4	92.6
15	65.43	63.54	1.89	37	2.73	97.27
19	962.74	936.37	26.37	29.7	2.68	97.32
Total	1284.31	1247.79	36.52	30.7	2.53	97.47

As a result, the buses, which are appropriate to apply DSM programs, can be determined before applying these programs. Furthermore, the buses can be prioritized to apply DSM programs.

6- Conclusion

In this paper, the appropriate network buses and appropriate networks to apply Demand Side Management programs are determined by investigating the impact of DSM programs on reliability index EENS. In order to achieve this goal, at the first step, networks are studied before applying DSM programs at two levels; HLI and HLII. Studies show that in some networks reliability indices are affected mostly at the HLI level. While in some other networks, reliability indices are influenced mostly at the HLII level. It means that in these networks, reliability indices are affected by transmission contingencies.

At the second step, a new approach is presented to structurally decompose reliability index EENS by using Monte Carlo simulation. EENS is decomposed into two terms. The first term indicates EENS which is caused by generation contingencies. The second term indicates EENS which is caused by transmission contingencies. Therefore, the proposed approach can be used to structurally analyze the reliability index of each bus and determine how much of EENS of each bus is caused by generation or transmission contingencies.

At the third step, first due to the concept of load shifting which is used in this paper as one of the DSM programs, and its impact on the Load Duration Curve, it is shown that the application of load shifting is effective in some networks and buses. These are the ones which their reliability index EENS is more influenced by generation contingencies. However; it is not effective in the ones which their EENS is more influenced by transmission contingencies. Therefore, the proposed approach can be used to indicate appropriate buses for applying load shifting. Then, Load Shifting program has been applied on the buses of IEEE-RTS and Khorasan 400 KV network and the appropriate buses is determined to apply DSM programs before applying these programs. The simulation results on these networks show the efficiency of the proposed approach. Moreover, the proposed approach could be used to evaluate complex network with more buses for application of DSM programs.

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