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Modeling and Quantification of Power System Resilience to Natural Hazards: A Case of Landslide

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ABSTRACT Power systems are stretched across thousands of miles of diverse territories, often in remote locations, to generate and transfer the energy to geographically dispersed customers. The system is therefore subjected to a wide range of natural hazards which could potentially damage critical system components and cause interruption of electricity supply in some areas. To improve system resilience against natural hazards, management frameworks are required to identify hazardous areas and prioritize reinforcement activities in order to take the most out of the limited resources.
Landslide is a natural disaster that involves the breakup and downhill flow of rock, mud, water, and anything caught in the path. It is a phenomenon frequently occurred in some parts of the world that could result in the failure of power transmission networks. Consequently, in this paper, a novel approach has been proposed that quantifies the landslide hazard, its damage to power system components, and the impacts on the overall system performance to prioritize reinforcement activities and mitigate the landslide vulnerability. The proposed approach is applied to a real power system and the obtained results are discussed in detail.

INDEX TERMS Landslide, natural disasters, power system, power system failure, power system management, reliability, resiliency, transmission system, vulnerability assessment.

I. INTRODUCTION

Power system is one of the largest man-made systems whose components are stretched across thousands of miles of diverse territories [1]. As a result, power systems are highly vulnerable to natural catastrophes as geographically dispersed components of interconnected power systems are subjected to a wide range of natural hazards. Considering the importance of electricity in the well-being of modern societies, the vulnerability of electrical infrastructure to natural hazards, and recent natural events such as hurricane sandy, resilience studies of power systems have gained significant attention in recent years [2]–[4]. In this context, resilience is defined as ''the ability to prepare for and adapt to the changing conditions as well as withstand and recover rapidly from disruptions'' [5]. Subsequently, A power system is considered to be resilient if it is able to anticipate, absorb, adapt to, and/or rapidly recover from a disruptive event [6].

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According to the definition of a resilient power system, resilient studies can be divided into different categories. In the first category, researchers strive to anticipate the impact of a natural event on the power system by modeling the occurrence of the event, identifying the components that are likely to be damaged and the overall operating condition of the system after the event [7]–[10]. Such resilience studies are complicated since predicting the intensity and spatio-temporal characteristics of a natural event and its impact on power system components are extremely difficult. Increasing the ability of the system to absorb natural events is another category of resilience studies. For instance, planning schemes for enhancing the ability of the system to absorb natural events are presented in [11], [12], while hardening and resource allocation are discussed in [13], [14]. Increasing the ability of the system to adapt to and rapidly recover from a natural event is another aspect of the power system resilience which attracts significant attentions in recent years. In this regard, using the islanding capability of microgrids for restoring the energy of interrupted customers is considered as a viable resilience enhancement solution by many researchers [15]–[18].

The Careful review of the literature reveals that most of the resilience studies are mainly concentrated on the absorption, adaption, and recovering aspects of resilience while the fundamental studies associated with anticipating a natural catastrophe and its impact on power system components have not received much attention. In addition, most of the resilience studies anticipating the occurrence of an event are concentrated on events associated with extreme weather [19] and other events are rarely studied.

A. MOTIVATIONS AND PAPER CONTRIBUTIONS

A landslide is the movement of rock, debris, or earth down a slope. It results from the failure of the materials which make up the hill slope and are driven by the force of gravity [20]. In areas with the high frequency of landslide occurrence, critical infrastructures are threatened by the event. A landslide is also a hazardous phenomenon that could damage the electrical energy infrastructures and initiate failures in power plants, substations, and transmission lines.

As mentioned, the areas prone to landslide occurrences could confront with curtailment of power supply due to failure in transmission networks. In this regard, from over 4000 large landslide events that have been reported in Iran, 1030 large landslides have historically been recorded in Zanjan and Ghazvin provinces. These events have incurred considerable damage to the people and infrastructures. Zanjan Regional Electric Company (ZREC) that is responsible for the production, transmission, and distribution of electricity in Zanjan and Qazvin provinces has also confronted with several landslides related outages. Consequently, ZREC is willing to invest in enhancing the system's resilience to landslides. However, most of the available literature is concentrated on extreme weather and does not address seismic or landslide hazards. In response, significant efforts have been devoted to introducing a novel resilience modeling and quantification framework to determine vulnerable system components and prioritize reinforcement activities. These efforts create the foundation of this paper. Accordingly, the resilience of the power system to landslide is, for the first time, modeled and quantified in this paper. The contributions of the paper can be summarized as follows:

- An applicable GIS-based hazard assessment approach is proposed to estimate the landslide hazard
- A novel approach is suggested that includes both components landslide damage possibility and associated outage consequences to assess the landslide damage risk and prioritize reinforcement activities
- The approach discriminates between substations/power plants and transmission lines due to their different geographical characteristics
- The proposed model is versatile enough to be applied to nation-wide power systems in order to identify vulnerable system components and sections

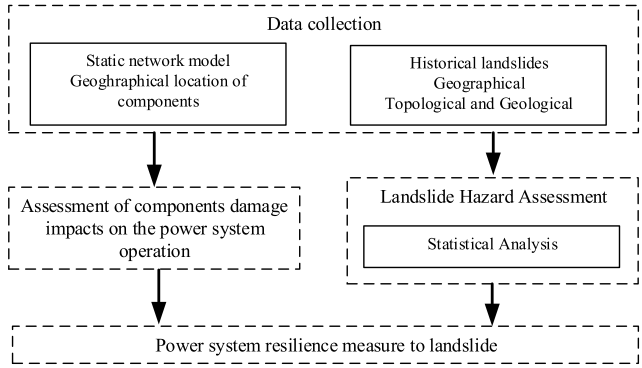

FIGURE 1. Outline of the proposed approach.

- The applicability of the proposed approach is demonstrated by applying the methodology to a real composite system.
- The developed framework would finally determine the areas that landslide could severely damage; which would respectively determine the energy systems that could be operated in the islanded mode.

It is expected that the final results of landslide hazard assessment provide a powerful analytical tool in the context of system reinforcement. In particular, the reinforcement budgets could be effectively concentrated on the most vulnerable components of the system. Besides, proper maneuvers and remedial actions could be planned to mitigate the overall impacts of landslide events. In addition, more accurate landslide hazard assessment could now be pursued in the design phase of new substations and transmission lines. It is noteworthy that the obtained results from the developed approach would direct the investments to areas that face loss significant economic losses due to landslide. As a result, these areas could be operated as microgrids with the ability to operate their critical loads with their own distributed power generation units. In this regard, the obtained results for ranking the critical areas in the power network would be utilized as the input information for research works that focus on determining critical load in each of the critical areas and modeling them as microgrids to be reliably operated in islanded modes.

B. METHODOLOGY OUTLINE

The key objective of this paper is to propose a new framework for quantifying the resilience of the power to landslide events. In this regard, the landslide hazard in the study area, initially, has to be extracted. Then after, the impacts of the landslide on the power system components have to be investigated and electrical consequences of the components' failure have to be estimated. Finally, landslide hazard and its consequences should be combined to provide a thorough measure of landslide resilience. Outline of the proposed methodology has been depicted in Fig. 1.

As mentioned, combining the effects of landslide happing on the infrastructures of power systems as well as the cost of infrastructures failure from loss of load perspective would facilitate the development of new indices for the measurement of the system resilience against landslide hazard. In this regard, this study requires analyzing a huge amount of data from geographical as well as electrical networks. In this regard, in order to provide a clear perspective, each step of the methodology is conducted by providing the real geographical and electrical data from the Zanjan and Ghazvin provinces as well as ZREC. Nevertheless, based upon the developed general approach, the proposed methodology could be employed to analyze areas prone to landslide occurrences in order to optimize the operational and planning procedures of the power system utilities.

The rest of the paper is structured as follows. Required data and the proposed method for landslide hazard assessment are both explained in Section II. As mentioned, for the first time, this paper aims to study the effects of landslides on power systems; therefore, modeling landslide occurrences seems to be an essential step in analyzing their effects on power system operation and planning. The incurred landslide damages to power system components and their associated consequences are studied in Section III. A novel approach for landslide vulnerability assessment is also presented in Section III. Finally, the proposed framework is applied on a network and the results are discussed in section IV.

II. LAND-SLIDE HAZARD ASSESSMENT

A landslide is defined as a downward movement of the ground in an unstable slope. Gravity is the fundamental force in a landslide event but geographical, geological, and topological characteristics such as slope, soil type, and also geology of the study area are the main contributing factors that determine the landslide hazard in an area [21]. In addition, since a landslide is usually triggered by an external stimulus like an earthquake, parameters measuring earthquake risks are also regarded as an important factor in landslide hazard assessment. Furthermore, some of the area characteristics such as temperature, vegetation, rainfall, etc. greatly depend on the elevation; consequently, elevation above the mean sea-level is also included in landslide hazard evaluation [21].

With the advent of modern computers and availability of digital maps, geologists can now analyze different properties of lands in areas where historical landslide events have occurred and identify the key characteristics of the susceptible strains. Consequently, landslide hazards can be estimated in unstudied locations by investigating these characteristics. Understanding factors that affect the susceptibility of landslide occurrence is a powerful tool that enables geologists to analyze a wide area with no recorded historical data and measure the landslide hazard. With the advent of Geographic Information System (GIS), advancement in satellite remote sensing, and improvement in computational capabilities of commercial computers, it is now possible to collect geographical data in a vast area and conduct far more detailed and accurate geographical analysis in the power system. Accordingly, Landslide hazard assessment could be pursued in a wide geographical area and the results could also be presented as a

TABLE 1. Recorded landslide events in various geological categories.

Geology Class	Recorded Events	percent	Recorded Events (in 100 Km^2)
I	0	0.00%	0.000
II	152	14.84%	2.213
III	176	17.19%	0.784
IV	51	4.98%	0.522
V	119	11.62%	0.661
VI	317	30.96%	0.941
VII	192	18.75%	0.495
VIII	2	0.20%	4.040
IX	15	1.46%	0.797
X	0	0.00%	0

TABLE 2. Recorded landslide events in various soil categories.

Soil Class	Recorded Events	percent	Recorded Events (in 100 Km^2)
1	1	0%	0.059
7	260	25%	0.814
8	99	10%	0.809
13	3	0%	2.711
14	125	12%	1.979
15	35	3%	0.356
16	0	0%	0.000
17	37	4%	0.306
18	422	41%	0.830
20	47	5%	1.200
Other Classes	0	0%	0.000

GIS landslide hazard map in which a hazard value is assigned to every geographical point within the study area [22].

A. COLLECTION OF GIS DATA AND INITIAL ANALYSIS

In this paper, landslide hazard has been assessed in a 156000 km^2 area located between coordinates 35° to 39° North and from 47° to 51° East which completely covers Zanjan and Qazvin provinces of Iran along with some parts of other provinces. In this area, 1030 large landslides have historically been recorded which is about a quarter of the entire recorded landslides in Iran.

A considerable amount of information is required to assess the landslide hazard in the area. Geographical locations of historical events, type of soil, and also geological characteristics within the study area were provided by Iranian Forests, Range, and Watershed Management Organization in GIS maps. Types of soil and geological characteristics are categorized into twenty and ten different classes respectively. These classes are introduced in the Appendix.

To study the effect of geology and soil properties on landslide initiation, historical data are analyzed; then, the number of landslide events in each category of soil and geology is extracted. The results are reported in Tables 1 and 2. It worth mentioning that the study area is not equally divided into different classes of soil/geology. Thus, in classes that cover a higher percentage of the study area, in the same condition, a higher number of recorded events would be expected. In this

TABLE 3. Recorded landslide events in different elevation categories.

Elevation (m above sea level)	Recorded Events	percent	Recorded Events (in 100 Km2)
<0	0	0%	0.0000
0-250	61	6%	0.1162
250-500	67	7%	0.1276
500-750	25	2%	0.0476
750-1000	32	3%	0.0610
1000-1250	75	7%	0.1429
1250-1500	132	13%	0.2515
1500-1750	188	18%	0.3582
1750-2000	274	27%	0.5220
2000-2250	125	12%	0.2381
2250-2500	37	4%	0.0705
2500-2750	5	0%	0.0095
2750-3000	1	0%	0.0019
3000-3250	1	0%	0.0019
3250<	0	0%	0.0000

regard, the number of recorded events in each soil/geology class is divided by the area covered by that specific category. Consequently, recorded events in 100 Km^2 are also extracted and reported in Tables 1 and 2. Subsequently, if landslide occurrence susceptibility in category A is higher than the susceptibility in category B; recorded landslides in 100 Km^2 for category A are expected to be higher than category B.

Analyzing the historical events reveals that areas with the geology of classes II, VIII, and VI are highly prone to landslide occurrence. It also shows the probability of landslide occurrence in the areas with soil classes of 13, 14, and 20 is much greater than the probability of occurrence in other regions.

Digital Elevation Model (DEM) maps are required to investigate the effect of elevation in landslide occurrence. DEM maps can also be implemented to calculate the slope of the ground and investigate the effects of slope on landslide susceptibility. DEM maps are extracted from the publicly available data of the Terra satellite [23]. In these maps, the surface has been divided into $20^m \times 20^m$ squares and elevation has been measured for each square with $7^m - 15^m$ accuracy. In fact, DEM maps are a set of x and y coordinates to which an elevation value is assigned.

As mentioned earlier, some terrain properties are related to the elevation. Thus, elevation at the location of historical landslides has been extracted and presented in Table 3. In addition, recorded events in 100 Km^2 are also calculated to offset the effect of elevation categories which covers a different portion of the study area.

Table 3 clearly shows that over 70 percent of the historical landslides are recorded in areas with elevations ranging from 1250 to 2250 meters above the mean sea-level. It also shows that landslide occurrence probability in the areas with an elevation higher than 2500^m and lower than 0^m is negligible.

A high-resolution DEM map can also be used to extract the slope map. The ground slope is the most important parameter which determines the landslide hazard in an area. In this regard, obtaining the map of the ground slope has remarkable

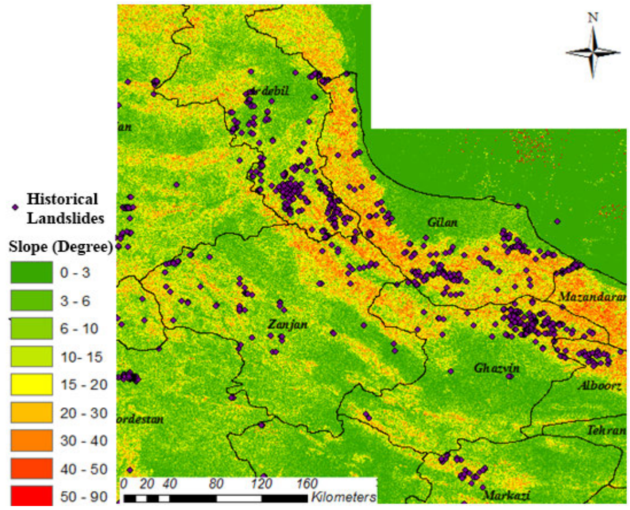

FIGURE 2. Slope magnitude map and location historical landslides.

TABLE 4. Recorded landslide events in different slope categories.

Slope (Degree)	Recorded Events	percent	Recorded Events (in 100 Km^2)
0-5	29	2.8%	0.051
5-10	167	16.2%	0.534
10-15	316	30.7%	1.837
15-20	280	27.2%	2.341
20-25	168	16.3%	1.891
25-30	57	5.5%	0.914
30-35	11	1.1%	0.284
35-40	2	0.2%	0.105
40-90	0	0.0%	0.000

importance in landslide hazard assessment. Theoretically, the gradient of the elevation map is the ground slope map. The gradient of the elevation is a vector with a specific magnitude and direction. In the context of landslide hazard assessment, slope magnitude is more influential than the slope direction. Subsequently, Terra DEM maps are analyzed and the slope magnitude map within the study area is extracted using the method proposed in [23]. The slope magnitude map and location of the recorded landslides are both illustrated in Fig. 2. Then, the ground slope in the location of the recorded landslide events has been examined and the results are reported in table 4.

As expected, Table 4 reveals that the landslide hazard is highly related to the ground slope. Most of the recorded events occur in terrains with a slope between 5 to 30 degrees. Table 4 also shows that landslide susceptibility in areas with the gradient less than 5 degrees or more than 30 degrees is negligible. If the ground slope is lower than 5 degrees, there is not enough downward force to move the soil and rocks toward the slope which reduces the landslide hazard. In contrast, in the ground with the gradient of 30 degrees or more, landslide hazard is insignificant because all movable materials have slipped down the slope and only solid, immovable materials have remained at the site.

TABLE 5. Euclidean distance of historical landslide to the nearest active fault.

Distance(km)	Frequency	Percent
0-5	355	34%
5-10	206	20%
10-15	131	13%
15-20	128	12%
20-25	59	6%
25-30	60	6%
30-35	7	1%
>35	85	8%

TABLE 6. Weights of equation (4).

Factor	*Weight*	
Slope	w_{Slope}	0.204396097
Fault Distance	$w_{\text{Distance to fault}}$	0.004009307
Elevation	$w_{\text{Elevation}}$	-0.035714091
Geology	w_{Geology}	0.03632252
Soil	w_{Soil}	0.089454055

The most devastating landslides are usually triggered by an external force such as earthquakes. Thus, the risk of an earthquake in an area has to be reflected in the landslide hazard assessment. An earthquake is caused by a sudden slip on an active geological fault. Therefore, Euclidean distance from each location to the nearest active fault is regarded as an earthquake risk in this paper. In this regard, a GIS map of active faults within the study area is obtained from the National Geoscience Database of Iran (NGDIR) and implemented in this study. The Euclidean distance of historical landslides to the nearest active fault has been extracted and reported in Table 5. The results show that there is an inverse relationship between the distance to active fault and landslide hazard in the study area.

B. HAZARD ASSESSMENT METHODOLOGY

A great amount of information has been collected and initially examined in Section II.A. In this section, the information is analyzed and a regression-based landslide hazard assessment methodology is implemented to measure the landslide hazard in the study area. In the proposed methodology, as shown in (1), the hazard index H in each location is estimated by the weighted sum of the intensities of associated factors in that specific location:

$$H = w_{\text{Slope}} \times S_{\text{Slope}} + w_{\text{Distance to fault}} \times S_{\text{Distance to fault}} + w_{\text{Elevation}} \times S_{\text{Elevation}} + w_{\text{Geology}} \times S_{\text{Geology}} + w_{\text{Soil}} \times S_{\text{Soil}} \quad (1)$$

In (1), w_i and S_i are the weight and the intensity of factor i respectively. Implementation of a regression-based approach necessitates that the hazard in an area expresses as a monotonic function of S_i. However, intensities of influential parameters in landslide hazard, as shown in II.A, don't exhibit this behavior. Thus, the regression approach implementation requires new intensity measures.

Landslide hazard in an area depends on both quantitative and qualitative factors. These factors are thoroughly categorized and reported in Section II.A. Based on Tables 1-4, the landslide hazard in the study area depends on the recorded events in 100 Km^2. Therefore, for geology, soil, elevation, and slope, recorded events in 100 Km^2 in each category are defined as the intensity factor of the associated category. In the case of distance to the nearest active fault, the percentage of recorded events in each distance can be defined as a measure of landslide hazard in each set. Definition of these new intensity measures initially fulfill the required monotonic intensity function and also simplify the calculation. For every location, one can evaluate the required parameters and extract the intensity measure through Tables 1-5.

To calculate the weights in the regression approach, there must be points in which landslide risk is high and also locations where landslide hazard is negligible. There are 1030 recorded landslides in the study area and the geographical location of these events can be regarded as the points where the landslide hazard is high. However, there is no reliable source to pinpoint areas in which landslide hazard risk is low. In this regard, geographical locations with a distance of more than 20km from recorded landslides are assumed to have low landslide risk. Then, 2075 random locations have been extracted from the low-risk areas and considered as low landslide risk locations. As a consequence, there are 1030 points with high landslide risk and 2075 locations with low landslide risk. Hazard index $H = 1$ is assigned to the high-risk points and $H = 0$ is assigned to the low-risk points. Weights in (1) are assessed so that it minimizes the (1) prediction error. Calculated weights are represented in Table 6.

Using the weights in Table 6 and (1), hazard index (H) within the study area can now be calculated. It's also clear that locations with a higher hazard index are more susceptible to landslide occurrence. However, a threshold level has to be defined so that landslide hazard in a region is considered dangerous if the hazard index in the area is larger than the threshold level. So, the hazard index for both low and high-risk points has been assessed and the results are shown in Table 7. The results show that 80 percent of the high-risk points have a hazard index of more than 0.3, while 78 percent of the low-risk points exhibit a hazard index less than 0.3. Besides, the hazard index in 86 percent of the low-risk points is lower than 0.5 while 73 percent of high-risk points have a hazard index of higher than 0.5. Accordingly, landslide hazard in an area has been divided into three clusters based on the hazard index value. Hence, areas with a hazard index lower than 0.3 are considered safe in landslide hazard assessment.

TABLE 7. Calculated hazard index for high and low-risk points.

Hazard index (H)	High-risk Points		Low-risk points	
	Recorded Events	Cumulative Percentage	Recorded Events	Cumulative Percentage
0 - 0.1	107	100%	1187	57%
0.1 - 0.2	40	90%	176	66%
0.2 - 0.3	59	86%	255	78%
0.3 - 0.4	71	80%	102	83%
0.4 - 0.5	102	73%	59	86%
0.5 - 0.6	244	63%	161	93%
0.6 - 0.7	230	39%	111	99%
More	171	17%	24	100%

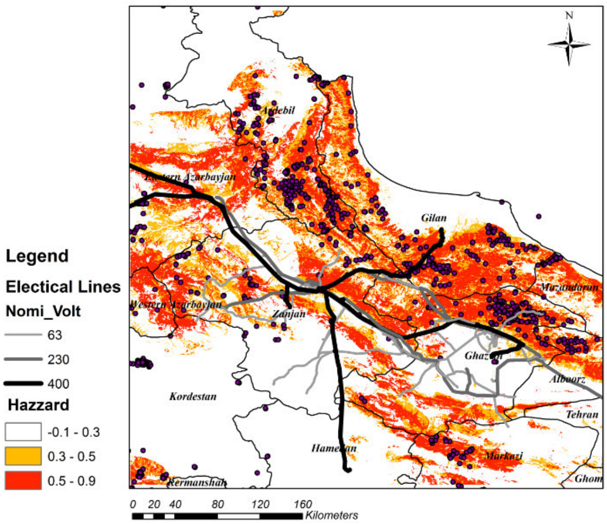

FIGURE 3. The GIS map of landslide hazard in the study area.

If the index were between 0.3 to 0.5 landslide hazard in the area is defined as medium and finally, areas in which hazard index is more than 0.5 are considered as hazardous areas. A GIS map of the landslide hazard in the study area is shown in Fig. 3.

III. POWER SYSTEM RESILIENCE QUANTIFICATION

So far, landslide hazard within the study area has been assessed and a hazard index has been defined for each location. In this section, a framework is proposed to assess the system landslide damage risk which is a measure of the system resilience towards landslide occurrences. This measure principally depends on the risk of failure of a component as well as its failure impact on the overall system operation.

A. ANALYZING THE IMPACTS OF COMPONENTS DAMAGE TO THE OPERATION OF THE POWER SYSTEM

To identify the landslide effects on a power system, in this paper, a formulation based on the optimal power flow (OPF) has been employed to evaluate the amount of load curtailment in each load point in a post-contingency condition. The proposed approach illustrated in (2) strives to minimize the amount of load curtailment while satisfying system constraints.

$$\min \sum_{i \in I^L} \left(PL_i^{normal} - Pl_i \right) \tag{2.a}$$

Subject to :

$$\text{FS}_i\left(\mathbf{P}, \mathbf{Q}, \mathbf{V}, \boldsymbol{\theta}\right) = 0 \quad i \in I^B \tag{2.b}$$

$$0 \leq PG_i < PG_i^{\max} \quad i \in I^G \tag{2.c}$$

$$QG_i^{\min} \leq QG_i < QG_i^{\max} \quad i \in I^G \tag{2.d}$$

$$0 \leq Pl_i \leq PL_i^{normal} \quad i \in I^L \tag{2.e}$$

$$Ql_i = \tan(\varphi_i) \times Pl_i \quad i \in I^L \tag{2.f}$$

$$0 \leq \left|S_j\right| \leq S_j^{\max} \quad j \in I^T \tag{2.g}$$

$$V_j^{\min} \leq \left|V_j\right| \leq V_j^{\max} \quad j \in I^B \tag{2.h}$$

In the above formulation, I^B, I^T, I^G and I^L are defined as the set of busbars, transmission lines, online generators, and load points, respectively. Active and reactive power production of i^{th} generator is represented by PG_i and QG_i, while its operational limits are shown by $PG_i^{\max}$, $QG_i^{\min}$ and $QG_i^{\max}$. Moreover, PL_i^{normal}, Pl_i and Ql_i are defined as the normal active, post contingency active, and reactive power consumption in load point i. The variable $\left|S_j\right|$ is responsible for apparent power flow while $S_j^{\max}$ shows the maximum allowable apparent power flow of the transmission line/transformer j. In addition, voltage magnitude of j^{th} busbar and its maximum and minimum limits are defined as $\left|V_j\right|$, $V_j^{\max}$ and $V_j^{\min}$, respectively. Finally, $\mathbf{P}$, $\mathbf{Q}$, $\mathbf{V}$, and $\boldsymbol{\theta}$ are the vectors of the injected active and reactive power, voltage magnitude, and voltage angle in all system busbars.

The objective function in (2.a) strives to minimize the overall amount of load curtailment in the system. (2.b) shows the complex power balance equations, while generators' active and reactive limits are included by equations (2.c) and (2.d). Moreover, it is assumed that the power factor in each system load would not change after the curtailment; therefore, the active and reactive power of each load point are restricted by constraints (2.e) and (2.f). Eventually, equations (2.g) and (2.h) are respectively modeled to enforce capacity limits and voltage magnitude boundaries associated with transmission line/transformers.

B. ANALYZING LANDSLIDE DAMAGE TO POWER SYSTEM COMPONENTS

In the context of landslide damage risk assessment, power system components can be divided into two major categories. Power plants and substations are located in a small-bounded area and so an approximate level of landslide hazard could be assumed within the location of each power plant or substation. On the other hand, a transmission line is spread across vast geographic areas; therefore, it experiences different levels of landslide hazard on its route. Consequently, damage risk evaluation of power plants/substations and transmission lines requires different procedures which are explained in the following subsections.

1) POWER PLANTS AND SUBSTATIONS LANDSLIDE DAMAGE RISK ASSESSMENT

A landslide is a local phenomenon that inherently causes damage to its surroundings. Landslide occurrences in the vicinity of a system component could initiate the component failure. Therefore, a component might be threatened by any landslides occurring in its proximity. As a consequence, in this paper, the average of the hazard index (H) within a radius of one kilometer is defined as a ''component average hazard index'' and denoted by h_j for component j.

As mentioned earlier, each substation or power plant is approximately subjected to the same level of landslide hazard; therefore, in this paper, it is assumed that the average hazard index of a power plant/substation could be estimated by the value of the average hazard index in its centroid. Since a power plant/substation is a surface bounded by a polygon, centroid could be calculated as the arithmetic mean position of all the points in the shape [24]. Moreover, it has been concluded in Section II.B that if a component average hazard index is lower than the threshold level ($h_j < 0.3$) then the landslide hazard is negligible; thus, these components are considered safe from landslide damages and excluded from the analysis.

Landslides could potentially damage all types of structures and system components. In this paper, the worst-case scenario, where a landslide event damages the most critical sections of a substation/power plant resulting in its total failure, is taken into account and the associated consequences are evaluated by the formulation stated in (2). On this basis, substation/power plant landslide damage risk ($LDR_j^{S/P}$) is a function of anticipated landslide hazard and its associated consequences; hence, $LDR_j^{S/P}$ is defined by the following equation:

$$LDR_j^{S/P} = h_j \times \sum_{i \in I^L} \left(PL_i^{normal} - Pl_i \right) \tag{3}$$

where h_j represents the average hazard index and the sum of curtailed load in all system load points is considered as the consequence of the event. Respectively, Landslide damage risk takes into account both aspects of a landslide event i.e. landslide hazard and associated electrical consequences.

2) TRANSMISSION LINES LANDSLIDE DAMAGE RISK ASSESSMENT

As a transmission line is spread at long distances, the transmission towers inevitably exposed to a wide range of landslide hazards. The proposed methodology in the previous section can be applied for evaluating the landslide hazard in the location of transmission towers; therefore, the component average hazard index can be implemented to identify towers located in hazardous areas. Prioritizing towers based on the landslide hazard is beneficial in managing the reinforcement activities by concentrating the budgets on the most vulnerable towers of the system.

Although the component average hazard index clearly shows the anticipated landslide hazard in the location of each transmission tower; it cannot simply be implemented in evaluating the landslide damage to a transmission line. Thus, it's necessary to define an additional index to compare different transmission lines from the landslide perspective. Towers of a transmission line are assumed to be in series and so the failure of each one can block the transmission of the electrical energy. In Section II, areas with a hazard index of larger than 0.5 are regarded as hazardous areas; thus, towers in that areas are greatly threatened by landslide events. Therefore, a new criterion is defined in equation (4) as the sum of the average hazard index of towers for which h_j is higher than 0.5.

$$R_j = \sum_{i \in I_j^{Tower} \cap\, (h_i > 0.5)} h_i \tag{4}$$

where R_j is defined as the j^{th} transmission line total hazard index and I_j^{Tower} represents the set of towers in line j. To compare the hazard in different lines, the above index has been normalized and represented by r_j as follows:

$$r_j = R_j / \max_{j \in I^T} (R_j) \tag{5}$$

The consequence of a transmission line failure depends on the network configuration and operating condition. Accordingly, the consequence of landslide originated outages have to be taken into account in landslide damage risk assessment. In this paper, equation (6) is employed to measure landslide damage risk of transmission lines (LDR_j^{line}):

$$LDR_j^{line} = r_j \times \sum_{i \in I^L} \left(PL_i^{normal} - Pl_i \right) \tag{6}$$

So far, landslide hazard has been assessed within the study area and a novel method has been proposed to evaluate the landslide damage risk. It is also worth mentioning that landslide damage risk can be regarded as a resilience measure. In the following section, the proposed approach has been applied to a real network and vulnerable components of the system have been prioritized.

C. MANAGEMENT OF THE SYSTEM CONSIDERING LANDSLIDE HAZARD

The proposed approach in this paper develops the component hazard index by considering the geographical characteristics of the area which is finally combined by the load curtailment caused by the power system's component failure in order to determine the resilience index. In this regard, the proposed methodology enables the utilities to rank the system components in order to direct the investment budget to reinforce the grid's infrastructure. On the other hand, utilities could define maneuver plans in order to decrease the risk of the system in case of landslide occurrences.

On the other hand, the increasing trend of integration of distributed energy resources (DERs) [25], as well as the introduction of microgrids, facilitate the islanded operation of the energy systems in case of grid's failure [26]. In other

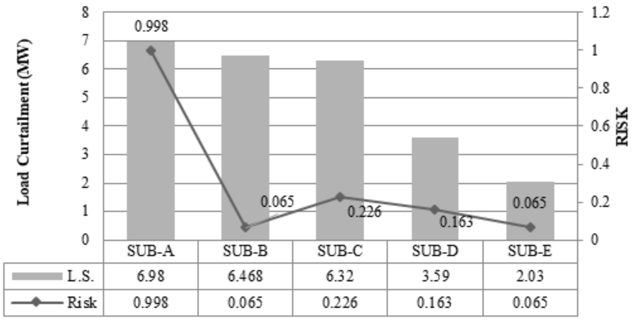

FIGURE 4. Average hazard index, curtailed load, and landslide damage risk of the most vulnerable substations.

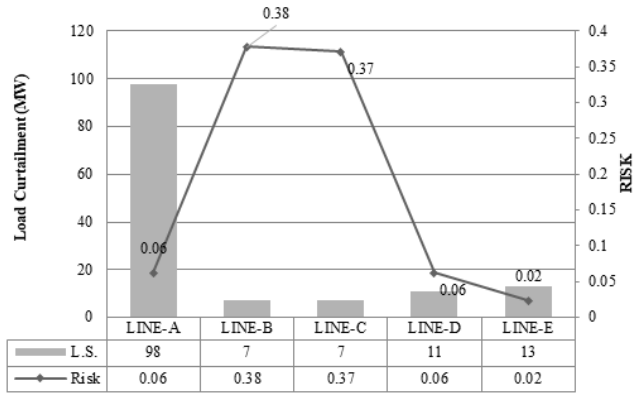

FIGURE 5. Normalized total hazard index, curtailed load, and landslide damage risk of the most vulnerable substations.

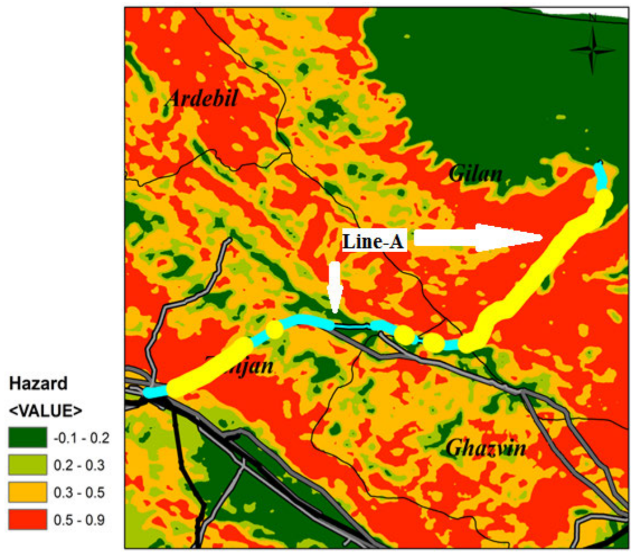

FIGURE 6. Classification transmission towers of line-A based on their exposure to the landslide damage.

words, the areas which are at high risk of load curtailment in case of landslide happening could be operated as microgrids and reinforced by installation of DERs [27]. In this regard, in case of landslide occurrences, a local controller could operate the microgrid in the islanded operational mode while utilizing the local distributed power generation units to supply the critical load demand. It is noteworthy that, in the normal operational mode, flexible resources, as well as renewable generation sources, would operate based on their objective (i.e. maximizing the profit); while, in case of power generation shortage, the system operator aims to merely supply the critical loads during the islanded operation. In general, the proposed scheme for evaluating the effects of landslide occurrences on the power system would enable the utilities to take into account the landslide hazard in their planning and operation procedures.

IV. RESULTS

This section presents the results of numerical studies conducted on the Electrical network in Zanjan and Qazvin provinces of Iran. Generation and transmission facilities in these provinces are mainly operated by ZREC. The company, at the peak, supplies 1074 MW of loads and operates one generation facility with the installed capacity of 648 MW. The utility also operates 213km of 400kV and 1305km of 230kV transmission lines along with four 400 kV, eight 230 kV, and thirty-nine 63 kV substations. It's noteworthy that hypothetical names for transmission lines and substations are used in this paper since the exact names and locations of substations and transmission lines cannot be disclosed because of contractual reasons.

In section II, the hazard index is developed and evaluated within the study area. In this regard, the results of the hazard index are demonstrated in Fig. 3. Since the proposed approach has been founded based on the average hazard index, initially, the centroid of each component (i.e. substations, power plants, and transmission towers) has been located and the average components hazard index (h_j) for each of them is evaluated.

The consequences of landslide occurrences on substations/power plants are evaluated using (2) and landslide damage risk has been assessed by (3). Results show that the average hazard index at the location of generation facilities are negligible and their operation are not threatened by a landslide event. On the other hand, the study reveals that some of the transmission and sub-transmission substations are located in hazardous areas. Average hazard index, associated curtailed load, and landslide damage risk of the most vulnerable substations are demonstrated in Fig. 4. The obtained results clearly show that both landslide hazard and substation failure consequence are necessary to be taken into account in power system vulnerability assessment.

Transmission lines are also studied in the landslide damage risk assessment. As mentioned earlier, the average hazard index has been evaluated for each tower and the total hazard index is evaluated for every transmission line. The outage consequence of each line is then assessed by (2) and combined by r_j according to (5) to extract the landslide damage risk of the transmission lines. Figure 5 represents the most vulnerable transmission lines within the study area.

One of the remarkable characteristics of the proposed method is its ability to prioritize transmission towers based

TABLE 8. Definition of geology classes.

Class	Geology
I	marl, gypsiferous marl, sandymarl and sandstone
II	Basaltic volcanic rocks
III	Andesitic volcanics, Dacitic to andesitic volcanic, Rhyolitic to rhyodacitic volcanosediment
IV	Light grey, thin-bedded to massive limestone, Conglomerate
V	Gneiss, anatectic granite, amphibolite, kyanite, staurolite schist, quartzite, and minor marble, Well bedded green tuff and tuffaceous shale, Teravertine
VI	Marl, calcareous sandstone, sandy limestone and minor conglomerate, High-level piedmont fan, and vally terrace deposits
VII	Marl, shale, sandstone and conglomerate
VIII	Gypsum
IX	Stream channel, braided channel and flood plain deposits, Swamp
X	Sand dunes and sand sheet

TABLE 9. Definition of soil classes.

Class	Type of soil	Class	Type of soil
1	Bad Lands	11	Salt Plug
2	Coastal Sands	12	Urban
3	Dune Lands	13	Water Body
4	Kalut	14	Alfisols
5	Marsh	15	Aridisols
6	Playa	16	Entisols/Aridisols
7	Rock Outcrops/Entisols	17	Entisols/Inceptisols
8	Rock Outcrops/Inceptisols	18	Inceptisols
9	Rocky Lands	19	Inceptisols/Vertisols
10	Salt Flats	20	Mollisols

on their exposure to landslide hazards. For example, the landslide hazard in the location of transmission towers of line-A is classified and depicted in Fig. 6. Thus, transmission owners can discriminate among the towers based on their vulnerability and spend available budgets on the most vulnerable sections of a transmission line.

V. CONCLUSION

Landslides are one of the most frequent natural disasters in some parts of the world, which threaten the safe and reliable operation of power systems. In this paper, a practical approach is introduced to evaluate the landslide hazard and identify components that are located in hazardous areas. In addition, a novel approach is presented where both damage possibility and failure consequences of each system component are taken into account to assess the landslide damage risk and prioritize reinforcement activities. The proposed approach is then applied to a real power system in Iran where components are prioritized based on their imposed risk to the overall system operation.

The proposed methodology can be regarded as a practical solution in both planning and reinforcing power system infrastructures. Initially, landslide hazard assessment pursued in Section II gives valuable insight to the hazardous areas and assists system planners to locate future infrastructures in safer places or enhance their design so as they can withstand possible landslide events. Besides, the proposed approach in Section III sheds light on the possibility of landslide damage and its associated consequences. This valuable information eases the reinforcement planning and aids the system managers to concentrate their limited budgets on the most important components of the system

APPENDIX

Tables 8 and 9.

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