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Modeling The Power Grid Network Of Iraq

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Abstract:

Recently, the theory of Complex Networks gives a modern insight into a variety of applications in our life. Complex Networks are used to form complex phenomena into graph-based models that include nodes and edges connecting them. This representation can be analyzed by using network metrics such as node degree, clustering coefficient, path length, closeness, betweenness, density, and diameter, to mention a few. The topology of the complex interconnections of power grids is considered one of the challenges that can be faced in terms of understanding and analyzing them. Therefore, some countries use Complex Networks concepts to model their power grid networks. In this work, the Iraqi Power Grid network (*IPG*) has been modeled, visualized and analyzed according to the theory of Complex Networks by representing the stations as nodes and the transmission lines as edges. This analysis is done by applying network metrics to the proposed national *IPG* network. Finally, this work provides a professional visualization of the generated network based on the demographic distribution and the accurate coordinates of the power stations. Thus, this proposed network is useful for the *Iraqi Ministry of Electricity*. Besides, it can be adopted by officials and specialists to understand, visualize and evaluate the performance of the current *IPG* network since it is still under development and modernization.

Keywords: Complex Networks, Network Metrics, Network Modeling, Power Grid Networks.

Introduction:

Analyzing power grid networks based on the concepts of Complex Networks has become a new trend and one of the most efficient tools. Complex Network Analysis (*CNA*) is a common research method in many disciplines used in studying social or historical networks. In addition, the use of big data in online social networks for ease of work and search, which is recently the focus of attracting internet users [1]. As well as disease prevalence, complex species interaction, logistics networks, Banking Systems [2], Crime Analysis [3], and more.

In Complex Networks, data can be formed as a network structure with nodes and edges. For instance, road networks [4], citation and co-authorship networks [5], cooperation networks, friendship networks, and gene networks [6]. In addition to all of that, power grid networks are our interesting field. In the context of this work, the power grid networks can be represented as the theory of graphs from networks science. Meaning that this type of method is modeled power grid networks as nodes and edges. These nodes and edges refer to the power stations and electric transmission lines respectively. Practically, this approach proves as one of the efficient ways of analyzing and visualizing the power grid networks. The **I**raqi **P**ower **G**rid network (***IPG***) has been used for investigating the connection patterns that might exist among power stations. For instance, two or more power stations are considered to be connected if they have at least one transmission line between them.

A simple example of how to generate and visualize the power stations' connection network as the graph is shown in Fig. 1. It presents a small part of the stations' connection of the *IPG* network by transmission lines. Thus, a small network of nine nodes is generated including fourteen edges among them which can be formed as follows:

#1: “Tabadol” connects to “Baawiza” by one bidirectional transmission line, 132 *kv* and 100 *MVA*.

#2: "Baawiza" connects to "Rasheedya" by one bidirectional transmission line, 132 *kv* and 100 *MVA*.
#3: "Rasheedya" connects to "Tabadol" by one bidirectional transmission line, 132 *kv* and 100 *MVA*.
#4: "Baawiza" connects to "Tahreer" by two bidirectional transmission lines, 132 *kv* and 100 *MVA* per line.
#5: "Tahreer" connects to "Mosul East" by one bidirectional transmission line, 132 *kv* and 100 *MVA*.
#6: "Tahreer" connects to "Qaraqush" by one bidirectional transmission line, 132 *kv* and 100 *MVA*.
#7: "Qaraqush" connects to "Mosul East" by one bidirectional transmission line, 132 *kv* and 100 *MVA*.
#8: "Mosul East" connects to "Intisar" by two bidirectional transmission lines, 132 *kv* and 100 *MVA* per line.
#9: "Intisar" connects to "Yarimja" by two bidirectional transmission lines, 132 *kv* and 100 *MVA* per line.
#10: "Intisar" connects to "Sharqiya" by two bidirectional transmission lines, 132 *kv* and 100 *MVA* per line.

Hence, the first step is to implement each power station as a node. After that, the edges are created based on transmission lines among them (see Fig. 1). In this example, the nodes refer to the High Voltage Substations (H.V.SS), which are part of Mosul Governorate stations. While edges are generated based on the robustness of the physical connection between them and depending on the weight of the transmission lines.

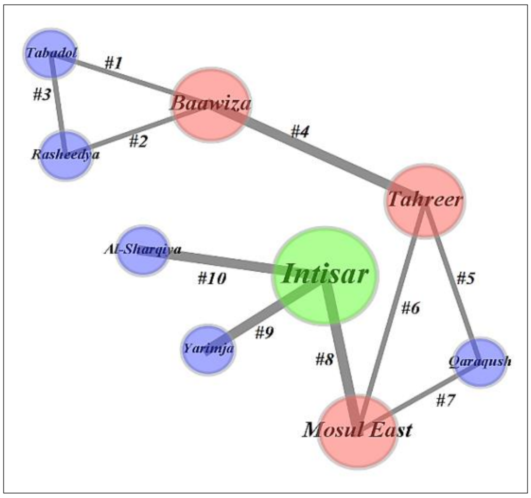

Figure 1. A simple example to visualize some Stations of Iraq and their connections

As mentioned above, the focus is on the Electricity field. It plays an effective and influential role in all activities in our lives. In addition, it contributes to getting radical solutions for our daily issues and its performance mainly influences the environment in all aspects of the world. More closely in Iraq, where Iraq is currently witnessing an evolution in many areas and specifically the production of the electricity (electricity industry) is the most important [7]. Furthermore, the power stations' distribution and their interconnections are necessary as electrical infrastructures for the community. These infrastructures are essentially interesting to understanding the theory of Complex Networks, as they are wide-ranging and expand in a decentralized manner [8]. Therefore, the applications of Complex Networks in power grid research have begun to rise over the past few years [9, 10].

Electricity Industry

The investigation of production quantity control in electric power stations has many factors. These factors impact on the construction of power stations according to geolocations and the availability of fuel resources used to operate these stations. For instance, the availability of fuel sources, proximity to electric transmission lines and distribution stations, as well as how close to consumers and public transportation routes. The consumption of electricity in Iraq has increased because of the inhabitants' growth, economic growth, and the significant increase in usage of electrical and electronic devices by consumers [11]. This leads to an increase in the economic development projects for serving and raising the Iraqi individual level gradually [7].

Several electrical infrastructures have been destroyed due to the recent events that Iraq faced as a result of the occupation of ISIS. Therefore, many challenges must be addressed. Such as growing load or delaying the completion of plans to overcome any trouble or blackout that suddenly happens. Moreover, according to the annual statistical report of the *Ministry of Electricity* of Iraq, the actual need to produce electrical energy to provide electricity to consumers in Iraq is 27,000 *MW* per day. Yet in fact, Iraq produces approximately 17,000 *MW* per day, which is much less than the required value [12]. Part of the remaining energy is compensated by purchasing electricity by transmission lines from Iran and Turkey [13].

Related Works:

The topological methods are focused on the structural vulnerability of the power grid networks. Whereas, a set of nodes is connected by a set of edges. These works recourse to the use of Complex Network measurements (metrics). For instance, node degree, betweenness centrality and clustering coefficient, etc. Thus electrical conceptions have not been considered [8,14]. In [15], the United States power grid networks were used for cascading failure analysis to identify significant nodes and edges. The authors collected the approach of Complex Networks with a more realistic load distribution between the neighboring nodes. In addition, the load on the influenced node was redistributed to its neighboring nodes not according to the degree of the node but according to the preferential probability. Moreover, in [16], the analysis of structural vulnerability in the interconnected power system has been studied. The authors investigated how interdependence between systems affects cascading behaviors and therefore changes the vulnerability of power networks. The investigation is focused on networks extracted from two interconnected power grids in the southeastern United States. These two networks are connected to each other via eight external lines.

In the past century, graph theory began to focus on statistics and analytics. Most studies use mathematical or statistical methods to model power grid networks [10]. Moreover, the Complex Networks approach has proven its ability to investigate and analyze power grid networks (see Table 1). Exactly in the 1960s, Paul Erdos et al. established the theory for graphs random as significant theoretical progress. As well as the ER random network mode modeled on the research in Complex Networks [17]. The power grid network is a complicated system including (Generators, Substations, and Transformers) connected by transmission lines in the length of hundreds of kilometers long [11]. Albert et al. built the North American power grid network model depending on the stored data in the POWER mapping system advanced by Platts (the energy information and market services unit of The McGraw-Hill Companies). It contains information about every power station, substation, and (115 − 765 *kv*) power transmission line for the North American power grid. The authors designed the power grid as a network of 14.099 nodes (1.633 of power plants and 2.179 of distribution substations) as well as 19.657 edges (transmission lines). Their model distinguishes three kinds of substations: Generators are the sources of power and Transmission Power Substations which transmit the power between high voltage transmission lines. Finally, Distribution Power Substations are at the outer edge of the transmission grid. The degree distribution of this network followed a Power Law $P(k) \sim k^{-\gamma}$ follows an exponential $P(k > K) \sim exp(-0.5K)$ [18].

The authors in [10,19,20] investigate the properties of three large regions of the world, North and Center China as well as the West American grid. The number of nodes and edges for each network with their statistical characteristic parameters are illustrated in Table1. Where K Sun analyzed and compared the metrics of these three networks in his work and found that the clustering coefficient of the Central China Power Grid increased only four times from the random graph with the same order and size [10]. While unbelievably, the West American grid is a finite-size effect. In addition, Rosato et.al. calculated the topological statistical characteristics of high-voltage power transmission networks in some of the European countries. For instance, the Italian-380 *kv*, the French-400 *kv*, the Spanish 400 *kv* power grids, and the fine-grain Italian grid which consists of electric transmission lines from (380 *kv* down to 120 *kv*, respectively) from available data [21].

In mapping, the topology of these Complex Networks there is continuously a hierarchy of high-degree nodes (hubs) that play an important part in the system. The Scale-Free networks were improved numerically and analytically which are more flexible to the loss of nodes randomly but vulnerable to attacks that target the high-degree nodes [22].

Table 1. Statistical Prosperities of some Power Grid Networks.

# of N	*# of E*	*C*	*O*	*<K>*	*L*	*Geographical area*	*U.H.V(kv)*
2379	2756	0.0044	48	2.32	21.08	Center China[10]	>110
8092	9018	0.0017	78	2.23	32	North China[20]	>110
4941	6594	0.08	46	2.67	18.7	West America[19]	115-765
14,099	19,657	-	-	-	-	North America[18]	115-765
127	171	0.156	25	2.69	8.47	Italy[21]	380
146	223	0.279	15	3.05	6.61	France[21]	400
98	175	0.316	11	3.57	4.92	Spain[21]	400
1926	2240	0.019	42	2.33	14.78	Italian fine-grain[21]	120-380

N: Node (Station); E: Edges (Transmission Lines); C: Clustering Coefficient; O: Diameter of the network; K: Average degree; L: Path length; U.H.V: Ultra-High Voltage.

According to the literature, it can be seen that Complex Networks can be considered as an effective tool for modeling power grids. Also, it can provide professional visualization and analysis approaches. Hence, the presented contribution in this work is to model the *IPG* network using Complex Networks concepts. Moreover, the properties of the generated network have been measured by using network metrics related to the theory of Complex Networks. The suggested model is of interest to the officials of the *Ministry of Electricity* in Iraq because it is used to understand and analyze the network performance. As well as to provide recommendations during failure situations. All computations of the topological statistical properties of the proposed model are mentioned in section 3.

Problem Statement and Contribution:

Several related literature studies have presented many approaches to power grid modeling but did not base on a specific deep study. Moreover, few studies have provided insight into the Spatio-temporal aspects of analyzing power grid networks. In addition, there are several gaps and limitations that are necessary to be filled. For instance, some of the literature lacks strategy plans to solve some problems that occur in the power grid. Nevertheless, this work indicates how to model and analyze the *IPG* network according to the Spatio-temporal aspects with fewer computations and minimal complexity. Evolving such approaches is a difficult task since it requires those interested to look deeply into the problem and consider the problem from various dimensions. Moreover, this paper aims to deal with cascading failure contingencies. As well as tries to improve the current *IPG* structural vulnerability model. The rest of this work is organized as follows; the next section includes the research methodology including the dataset collection, network metrics, and Iraqi Power Grid network modeling. Section 3 contains the results obtained from the analysis approach, discussion, and recommendations. Finally, the whole work is concluded in Section 4.

Research Method:

This section explains the details of the research methodology used in this work. It includes how to collect the dataset used to model the *IPG* network. As well as network metrics, modeling, and visualization of the *IPG* network by using Complex Network Analysis and their tools. In Complex Networks, there are several metrics used for measuring certain characteristics within any network. These metrics differ according to some criteria. Some of these are used for measuring the overall performance of the whole network. Others are used for measuring the performance of an individual node within a network. These are explained below in detail in the network metrics. Moreover, the used dataset is visualized by graphical representations such as graphs and pictograms. The data visualization tool allows us to understand the data and the patterns in data. It enables decision-makers to see the analysis in a visual form. Moreover, it allows decision-making and defining courses of action based on the visualization.

Data Collection

The dataset collected in this work is from the annual statistical report of the *Ministry of Electricity* of Iraq [12]. In addition, the coordinates (*latitude* and *longitude*) of each station along with its location have been collected by Google Earth ArcGIS and Google Earth Pro to closely illustrate and measure the attributes of each power station. Information about each station was collected according to its voltage, design capacity, production capacity, region, and type of each station. In addition, the data about each transmission line was collected according to its weight, voltage, capacity, and length. Where their weights reflect the power consumption of the station compared to the other stations.

After the dataset was collected completely, it was converted into two Excel files (type of .csv). The first file is for nodes (power stations) including all their attributes (station ID, name, voltage, latitude, longitude, design capacity, production capacity, number of units, type, and area). While the other includes the edges containing the transmission lines connecting the stations with all their attributes (voltage, weight, capacity, and length).

Network Metrics

The structure of the proposed model called the **I**raqi **P**ower **G**rid network (***IPG***) was based on the collected dataset and it can be formed as a graph G (N, E) [23,24]. Where N indicates the network nodes (power stations) and E indicates the relationships among them (transmission lines). Based on the nature of the relationship between two nodes. A weight W can be assigned to each edge within a graph (network). Each element $n_i \in N$ is either a substation, transformer, or consumption unit of an actual power grid. There is an edge $e_{i,j} = (n_i, n_j) \in E$ between two nodes if there the elements represented by n_i and n_j are connected with a physical cable directly. Moreover, using graph properties is an interesting way to classify the power grid under analysis [9]. These metrics can provide results from the analysis of the power stations and transmission lines. The physical elements or metrics of the network performance are evaluated according to the following two levels, *Network-level* and *Node-level metrics* [25]:

***(A) Network-level metrics*:** A specific feature of the entire network architecture can be measured and includes the following:

***Clustering coefficient (C)*:** Reflects the direction of network nodes to cluster among themselves. The value of *C* depends on the number of triangles formed by a specific node. In a Power Grid, *C* measures the tendency of stations and can be the local clustering coefficient (C_i) or global clustering coefficient (C_G). The formula can be defined as follows [26]:

$$C_i = \frac{2|\{l_{ik}: n_j, n_k \in N_i, l_{ik} \in E\}}{ki(ki-1)} \quad \ldots\ldots 1$$

Where l_{ik} is the transmission line between the stations n_j and n_k. N_i is the total grid stations and k_i is the neighbors' stations in the grid. Moreover, the average clustering coefficient (global clustering coefficient) (C_G) can be defined as follows below [5], where N is the number of stations of the grid and C_i is defined in Eq. 1.

$$C_G = \frac{\sum_i^n C_i}{N} \quad \ldots\ldots 2$$

***Average Path Length (l)*:** The average distance between two stations indicates the path length *L*. All the possible pairs of stations in the power grid are defined as the average number of paths for all the shortest paths between pairs. In the *IPG* network, the average shortest distance among stations is shown as follows below [27], where d_{ij} is the length between the nodes (the stations) *i* and *j*.

$$l = \frac{1}{n(n-1)} \sum_{i \neq j} d_{ij} \quad \ldots\ldots 3$$

Diameter (O): It refers to the longest path among all the shortest paths in any network [27]. In the *IPG* network, the distance between the farthest stations is been calculated.

Density (D): The number of edges divided by the total number of possible edges. Whereas, possible edges mean the maximum number of edges physically and mathematically allowed to the given number of vertices. Meaning, it is defined as the ratio of the number of edges of the network to the number of possible edges in that network and it can be defined as follows [26]:

$$D_G = \frac{2(E(G))}{N(N-1)} \quad \ldots\ldots 4$$

***(B) Node-level Metrics*:** The performance of nodes in a network can be evaluated and includes the following:

***Degree Centrality* (C_D)** of a node refers to the number of node connections in a network [5]. Meaning, the sum of edges connected to a particular node (also called the degree of a node). In-network visualization, the size of the vertices is decided by the degree.

***Betweenness Centrality* (C_B)** is counted by the number of the shortest path between any pair of nodes passing through the node. Meaning, it reflects how well a node is located in transmitting and consuming the electrical power within a network. This means that high C_B values reflect a high level of influence for a node in a network. As well, vertices with high C_B are gatekeepers controlling the flow of information and influencing passing between others. Although one vertex has a low degree of centrality, it can have a great influence on the entire network with its high C_B. The C_B of node *j* can be formed as follows [4,26]:

$$C_B(j) = \sum_{i \neq j \neq k} \frac{\sigma_{ik}(j)}{\sigma_{ik}} \quad \ldots\ldots 5$$

Where σ_{ik} denotes the shortest path between the stations *i* and k and σ_{ik} (*j*) denotes the number of transmission lines that lead to station *i.*

***Eccentricity* (*E*)** in our work reflects the longest distance of transmission lines from a station to any given station in the network. The eccentricity values for all stations were calculated using the following equation [4,25].

$$E_t = \frac{1}{\max(dist(k,t) : k \in T)} \quad \ldots\ldots 6$$

***Eigenvector Centrality* (X_i):** Nodes having neighbors with more degree centrality have more power than nodes having neighbors with less degree centrality. Eigenvector centrality indicates the sum of scores of its neighbors' degree centrality. It can be calculated by the formula below [25,28], where i denoted to a station, N_i the adjacent stations, $A_{i,j}$ is set to 1 when station i has a direct transmission line to station j, and 0 otherwise. The term λ is constant and X is the obtained score for a given station.

$$X_i = \frac{1}{\lambda} \sum_{j \in N_i} X_i = \frac{1}{\lambda} \sum_{j \in G} A_{i,j} X_j \quad \ldots\ldots 7$$

***Closeness Centrality* (C_C)** refers to the summation of the shortest paths to a node with other network nodes [5]. It shows how close a station is to other stations in the *IPG* network. As well as it can be determined as below, where (ij) is the distance between the stations i and j as mentioned above.

$$C_c(i) = \frac{N-1}{\sum_i d(ij)} \qquad \ldots\ldots 8$$

Iraqi Power Grid Network Modeling

The structure of the suggested model network is an undirected, weighted, static and scale-free network graph. It is considered a graph G (N, E) [24,25], where (N) is a set of nodes and (E) is a set of links among them. As well, it includes 310 nodes and 432 edges connected with them. Each node (N) represents a power station that includes either transformer, generator, or substation, while the edges (E) represent the electrical transmission lines among the stations. Connecting transmission lines depends on how close the stations are, the terrain, population density, and the importance of the station. Gephi is used to visualize the network depending on the station's coordinates (nodes) and the transmission lines between them (edges) [29].

This proposed model distinguished three kinds of power stations. They are *Generation Power Stations* (also called Power Plants) which are the sources of power, *Ultra-High Voltage Station_400* (Super Grid Station) that reduce ultra-high voltages_400 *kv* to high voltages_132 *kv* and *High Voltage Substation_132* (Substation) that reduce high voltages_132 *kv* to medium voltages 33kv and to low voltages 11*kv* respectively that provides the distribution power stations and the consumers with Electrical energy directly [11]. Some considerations have been taken, such as:

The Distribution Power Stations that include the outer edges of the transmission grid and the centers of local distribution grids are been neglected in this model because of their complexity and the difficulty of obtaining sufficient information about them.

The overall of Iraqi power stations in this proposed model is about 310 Power Stations; as 57 nodes are Generation Power Stations, and 19 nodes are Super Grid Stations, with 234 nodes classified as Substations.

The transmission lines that straight bind between two connected stations (nodes) have been merged in a single connection line (Bidirectional line). Thus, the *IPG* network model can be considered as a weighted, undirected, and sparse joint graph with N nodes and E edges. Therefore, it defines an NxN matrix X_{ij}; if a straight path is between i and j, then X_{ij} =1, otherwise X_{ij} =0.

The Generation Power Stations in Iraq depend on two main sources for operating which are; *Fossil Energy* represented by oil and natural gas, with 81% of the production of electricity capacity. As well as *Renewable Energy* is represented by dam water and solar energy with 19% of the production of electricity capacity. The stockpiled power ensures transmission of electricity easily in circumstances where conduction may disrupt or be unsuited [30,31,32]. In Iraq, the greatest dependence is on dams (Hydro Energy).

Moreover, these Generation Power Stations are divided into several types of stations depending on their sources [12]; ***Th**ermal **P**ower **S**tations_**Th.P.S***, that work on fossil fuels (Pure Oil), ***G**as **P**ower **S**tations_**G.P.S***, that work on fossil fuels (Natural Gas), ***D**iesel **P**ower **S**tations_**D.P.S***, which is based on Gas Oil, and finally ***H**ydro **P**ower **S**tations_**H.P.S***, depend on Renewable Energy (Hydro Energy from Dam).

Results:

The map of Iraq's borders with its governorates is presented in Fig. 2. While Fig. 3 presents the geographical distribution of the Iraqi power stations according to the coordinates of each station from north to south of Iraq as extracted from Google Earth Pro.

Furthermore, after the *IPG* network visualization is generated as shown in Fig.4, the properties of measuring the geographical nature of the *IPG* network are shown in Table 2. These metrics used *latitude* and *longitude* in their calculations.

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Figure 2. The map of Iraq

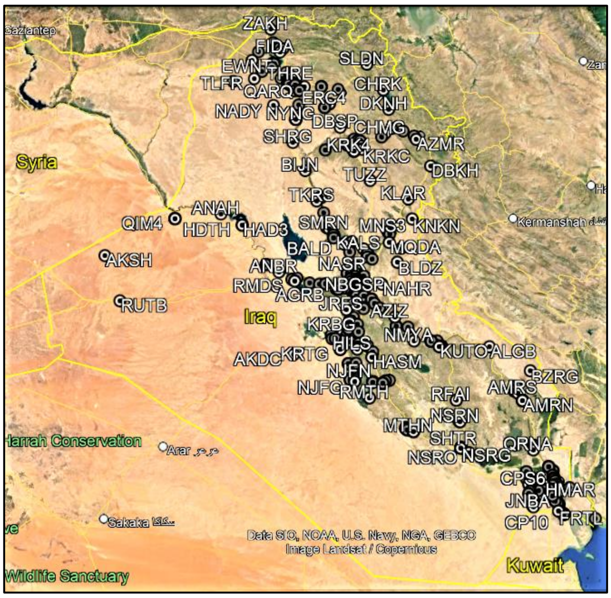

Figure 3. Geographical distribution of the Iraqi power stations

Table 2. Geographical Properties of Metrics for *IPG* Network

Statistical Metrics	Degree
Direction	*SSE* (148.44 degrees clockwise from North)
Average distance	29.52 *km*
Standard deviation	33.69 *km*
Magnitude	2904.54 *km*

In addition, many statistical network metrics for the *IPG* network are measured, these properties are summarized in Table 3. As mentioned, the number of stations is 310 connected by 432 transmission lines based on the weight of the line. According to the statistical properties of the network, it reflects a high diameter level of 48, the density of the network is 0.009, an average degree is 2.787, an average weighted degree is 4.658, an average path length is 19.561 and the average clustering coefficient is 0.205.

Table 3. Statistical Metrics of the Iraqi Power Grid Network

# of N	***# of E***	***C***	***O***	***D***	***<K>***	***W***	***L***
310	432	0.205	48	0.009	2.787	4.658	19.561

N: Node (Power Station); E: Edges (Transmission Lines); C: Avg. Clustering Coefficient: Diameter of the network; D: Density of network; K: Average degree; W: Average weighted degree; L: Avg. Path length.

As mentioned, the visualization of the network in Fig. 4 was performed based on distinguishing each station with its exact coordinates on the map (*latitude* and *longitude*) and depending on the Voltages for both stations and transmission lines. The colors of the nodes (red and black) in the network represent the *Ultra- High voltage stations* (Super Grid) and *High voltage* (Sub-Stations), respectively. The size of the node reflects the load level of the station. Meaning that the higher the size, the heavy load of the station. This visualization is dropped on the map of Iraq as clearly shown in Fig. 5.

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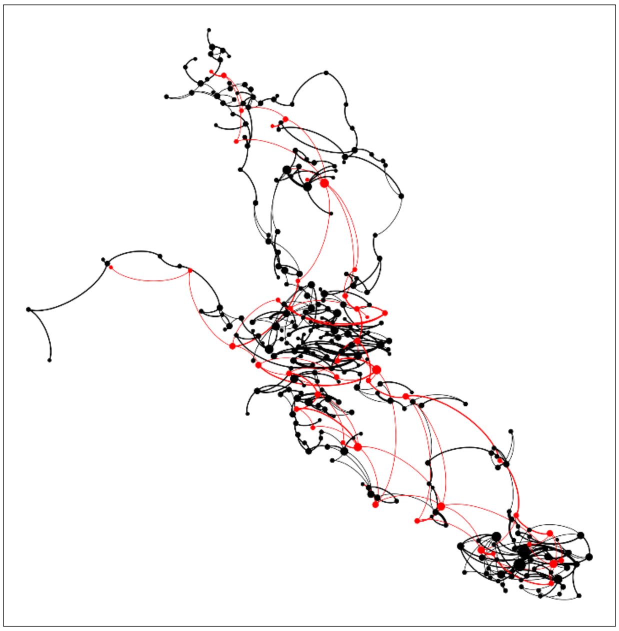

Figure 4. ***IPG*** **Network Visualization**

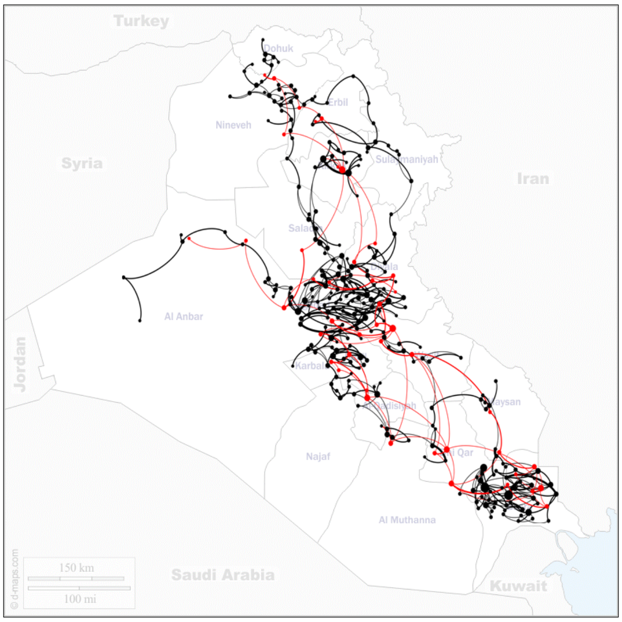

Figure 5. ***IPG*** **Network Visualization on Iraqi Map**

Network Metrics Centralization

In order to measure the performance of the stations within the network, the chosen metrics below enable us to discover the highest important and most effective stations. In addition, Figures (6,7,8) depict that the colors of the nodes reflect the different weights of the stations and the size of the nodes based on the value of the centrality type chosen. The metrics used are:

A) Betweenness Centrality Metrics

The highest *Betweenness Centrality* levels of the stations are presented in Table 4. It is an indication of the connection of the station to any two groups of interconnected stations (the shortest path).

In addition, it is very influential and important in terms of the electrical power flow of the interconnected groups. For instance, the connection of a governorate network with another governorate. That is, this effective station controls the flow of electric power from one area to another. Although it has a low degree of centrality C_D, it can have a significant impact on the whole network with its high *Betweenness* C_B. The visualization of the highest *Betweenness Centrality* for effective stations in the *IPG* network is shown in Fig. 6.

Table 4. The Highest *Betweenness Centrality* Stations in *IPG* Network

#	Eff. Station	B	Governorate	D.C.	P.C.	Voltage	T	Degree	Weight
1	Baghdad South	0.477	Baghdad	1000	660	132	H.V.G	4	8
2	Rifaai	0.474	Nasiriya	315	265	132	H.V.SS	3	5
3	Suwaira	0.452	Kut	176	155	132	H.V.SS	2	4
4	Zubaidia	0.448	Kut	2820	2061	132	TH.P.S.	4	5
5	Al-Djail	0.413	Salahadin	189	165	132	H.V.SS	4	4
6	Baghdad West	0.358	Baghdad	1250	1100	132	H.V.G	7	12
7	MullahAbdulla	0.314	Kirkuk	282	111	400	G.P.S	7	11
8	Old Amara	0.281	Amara	233	205	132	H.V.SS	3	5
9	Qurna	0.254	Basra	1250	1100	132	H.V.G	2	6
10	Kirkuk 400	0.251	Kirkuk	1000	880	400	U.H.V.S	7	7
11	Shergat	0.181	Salahadin	189	165	132	H.V.SS	2	4
12	Gayarah	0.176	Nineveh	189	165	132	H.V.SS	2	4
13	Shamiyah	0.156	Kadisiyah	270	240	132	H.V.SS	3	5
14	Baghdad East	0.126	Baghdad	1000	880	132	H.V.G	4	7
15	Diyala 400	0.116	Diyala	1000	440	400	U.H.V.S	3	4

B: Betweenness; D.C: Designed Capacity (MVA); P.C: Production Capacity (MVA); Voltage (KVA); T: Type of station

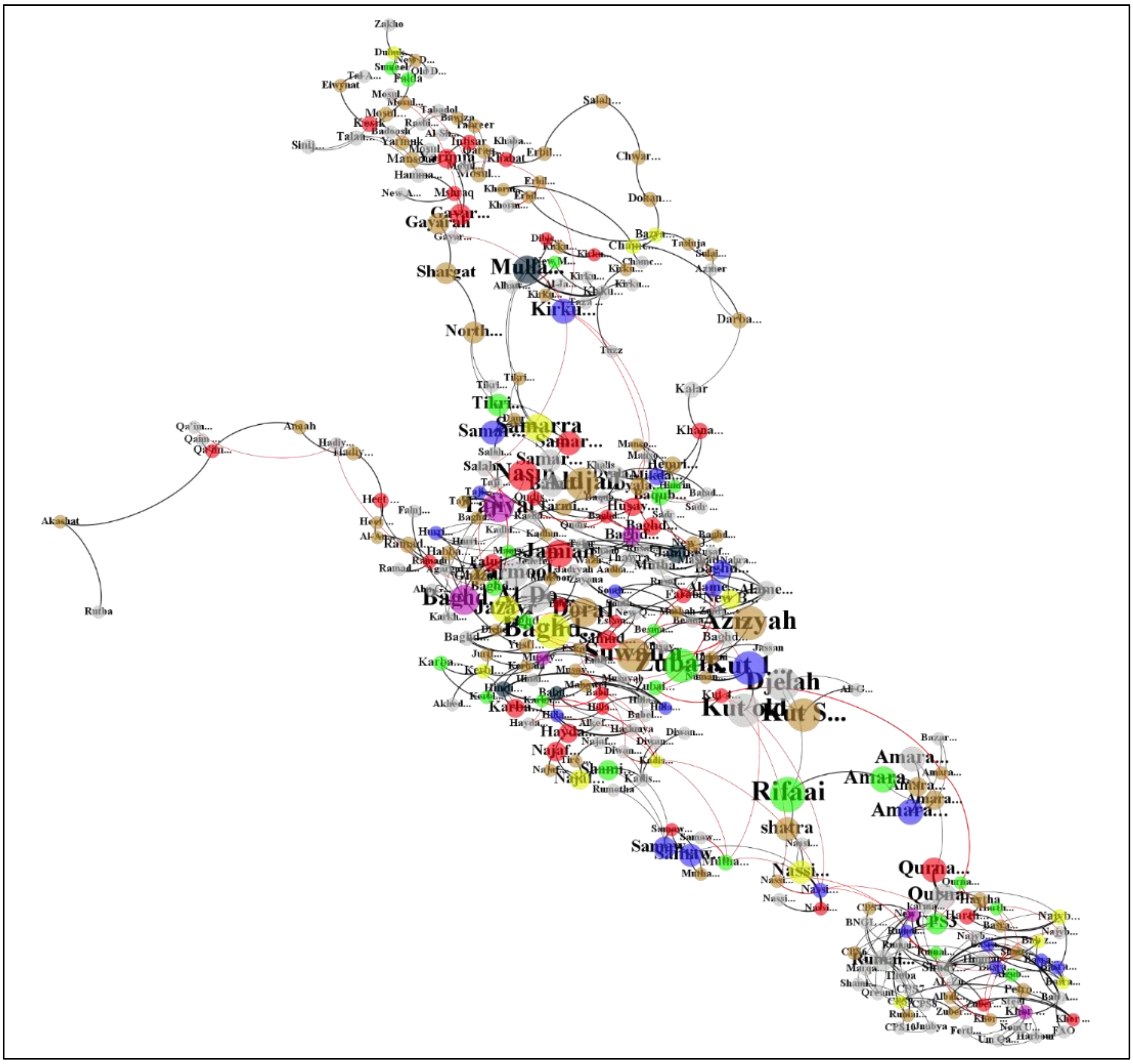

Figure 6. Visualization of the *IPG* network according to *Betweenness Centrality* of nodes.

B) Eccentricity Centrality Metrics

It reflects the maximum path (transmission lines) from a given station to another station in the network. Table 5 denotes the top *Eccentricity Centrality* of power stations as shown in (Fig. 7). These stations consider within the outliers stations.

Table 5. The Highest *Eccentricity Centrality* Stations in *IPG* Network

#	Station	E	Governorate	D.C.	P.C.	Voltage	T	Degree	Weight
1	New Um-Qasir	48	Basra	189	165	132	H.V.SS	2	2
2	Zakho	48	Duhuk	126	110	132	H.V.SS	1	2
3	Old Duhuk	48	Duhuk	126	110	132	H.V.SS	1	2
4	Eskandarya	47	Babil	252	220	132	H.V.SS	3	4
5	FAO	47	Basra	189	165	132	H.V.SS	2	3
6	Hindiya Barage	47	Babil	15	10	132	H.P.S	1	2
7	Akhedr Cemnt	46	Karbala	126	110	132	H.V.SS	1	2
8	Tal Abuthahir	45	Nineveh	189	165	132	H.V.SS	1	2
9	Qudis G.P.S.	40	Baghdad	1894	991	400	G.P.S	2	3
10	Qa'im 400	40	Anbar	1000	600	400	U.H.V.S	1	1

E: Eccentricity; D.C. Designed Capacity (MVA); P.C.: Production Capacity (MVA); Voltage (KVA); T: Type of station

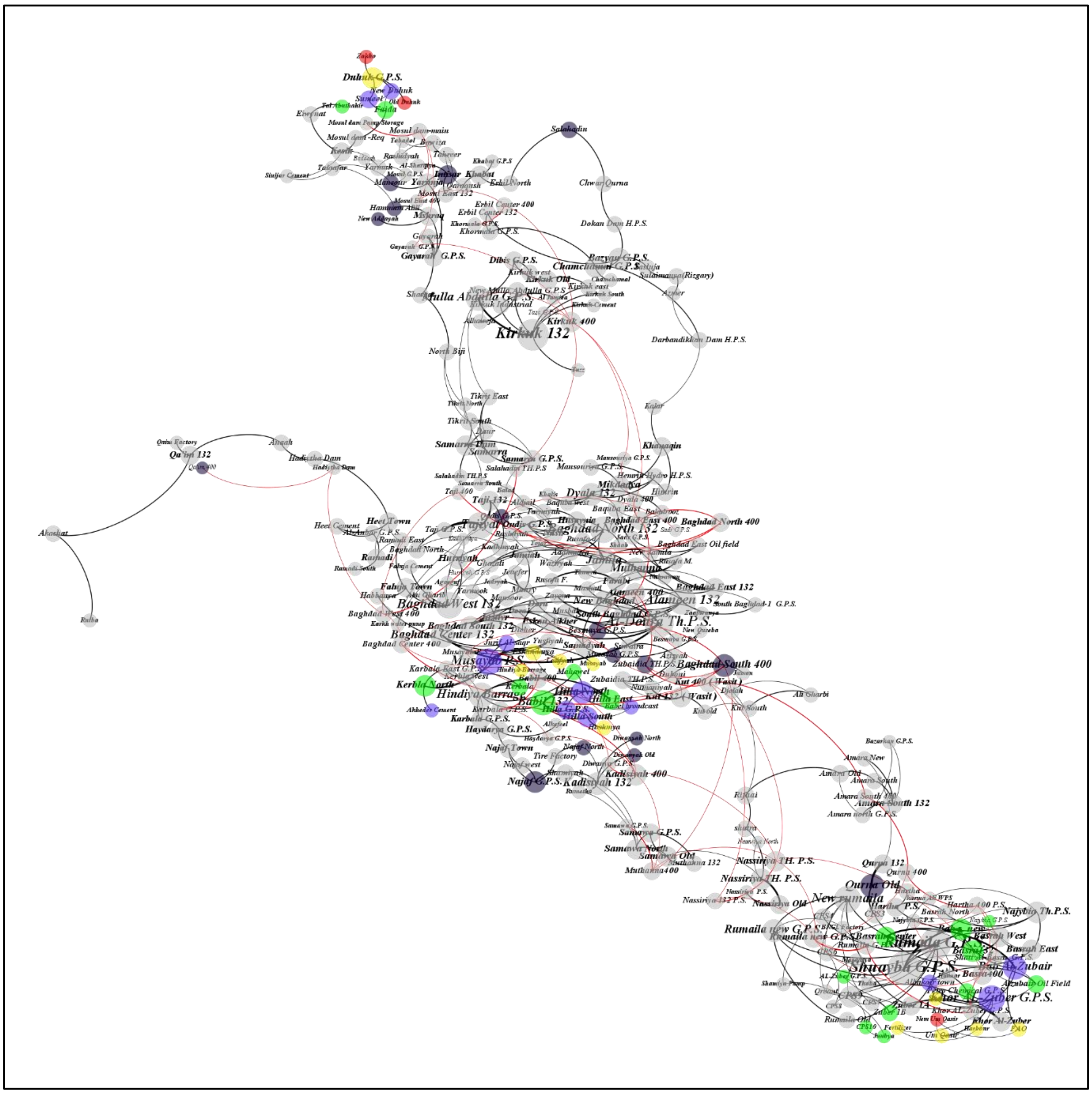

Figure 7. Visualization of the *IPG* network according to *Eccentricity Centrality* of nodes.

C) Eigenvector Centrality Metrics

It shows the station that is connected to the stations with high connections and high effectiveness in the network. Table 6 depicts the *Eigenvector Centrality* stations in the *IPG* network.

These stations represent the most effective, dependable, and reliable stations that lead to a higher connection with other stations. Fig.8 shows the visualization of the top effective stations in the *IPG* network depending also on the weight of the stations and the *Eigenvector* of the node size.

Table 6. The Highest *Eigenvector Centrality* Stations in the *IPG* Network

#	Effective Sta.	E.C.	Governorate	D.C.	P.C.	V.	T	D.	W.
1	Rumaila	1.0	Basra	1810	972	132	H.V.G	11	16
2	Shuayba	0.990	Basra	47	36	132	G.P.S	11	18
3	Nasiriya	0.445	Nasiriya	988	433	132	TH.P.S	6	7
4	Mulla Abdula	0.414	Kirkuk	282	111	132	G.P.S	7	11
5	Baghdad Sou.	0.407	Baghdad	1000	660	400	U.H.V.S	7	9
6	Kadisiyah	0.347	Kadisiyah	1250	1100	400	U.H.V.S	6	8
7	Babil	0.316	Babil	1000	880	132	H.V.G	6	11
8	Muthanna	0.309	Samawa	1000	880	400	U.H.V.S	4	5
9	Samraa	0.302	salahadin	189	165	132	H.V.SS	5	8
10	Kut (Wasit)	0.245	Kut	1000	660	400	U.H.V.S	4	6

E.C. Eigenvector Centrality; D.C. Designed Capacity (MVA); P.C.: Production Capacity (MVA); V: Voltage (KVA); T: Type of station; D: Degree; W: Weight.

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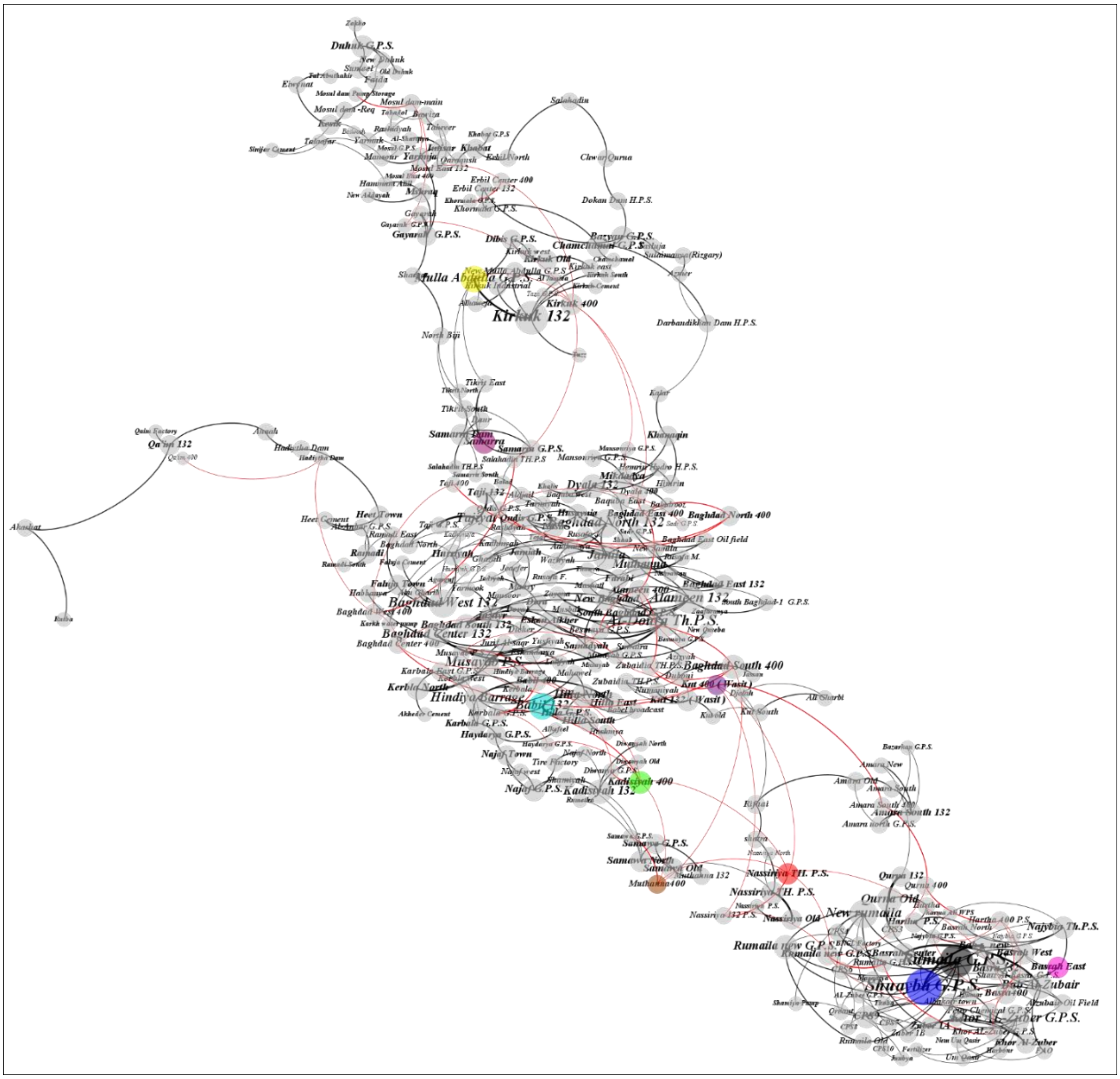

Figure 8. Visualization of the *IPG* network according to *Eigenvector Centrality* of nodes

Discussions:

The amounts of electrical power produced in Iraqi power stations change from one station to another. This is due to the difference in the number of active generating units for the station on the hand, and the variation in production factors on the other hand. For instance, some stations have one generating unit as in Nasiriya and Samawa stations. While the other station has fourteen generating units as in Al-Quds station.

Moreover, many factors affect the actual production quantity of power stations. This impact on the production level of each station appears by comparing specific years or seasons. The most important of which is a variation of the quantities of fuel needed for production, the different types of liquid fuel in which the stations operate and the exposure of units to a specific malfunction that requires a period for maintenance, etc. In general, the change in the number of actual operating units leads to a difference in the percentage of energy produced, which is called the economic utilization factor.

Conclusions:

This model can be used as a theoretical topological model to help engineers and specialized scientists measure the effectiveness of the *IPG* network. In this work, the power stations and transmission lines of Iraq have been modeled using the theory and analyses of Complex Networks as a kind of weighted and undirected network based on network and node metrics. Moreover, the analysis approach was based on the statistical properties of network metrics. These metrics are used to evaluate the network performance. The generated model represents the *IPG* network. The nodes represent the power stations, while the edges refer to the electrical transmission lines that connect among the stations. As mentioned above, the dataset was collected from the annual statistical report of the *Ministry of Electricity* of Iraq including 310 stations and 432 weighted edges (represent transmission lines). At last, some conclusions have been reached to assist researchers and investigators who are interested in this field.

After modeling the *IPG* network, projecting it onto the map of Iraq and visualizing it by Gephi, several things have been noted. Such as, after computing utilizing centralization criteria according to Complex Networks theory, the network performance has been evaluated. For instance, the high-impact power stations were sorted in the terms of *Betweenness* and *Eigenvector Centralities*. While the lowest effective stations (outlier stations) were sorted in terms of *Eccentricity Centrality*. In addition, the computation of the degree distribution and weighted degree distribution for the whole network is mentioned and has been taken into consideration. Furthermore, it has been concluded that the establishment of power stations and their transmission lines are distributed according to population density. Also to the locations of commercial, industrial and agricultural areas. These sites consume a sufficient amount of electrical energy for the purpose of their sustainability.

Moreover, after measuring and calculating the *IPG* network properties in terms of network metrics, the strengths and weaknesses of the Iraq network have been identified. These properties (weaknesses and strengths) are presented to the engineers specialized because they are so familiar by the engineering vision. In terms of strengthening the internal units of the stations or the lines of connection between them. The calculation of the national *IPG* network properties is of great benefit for identifying important power stations with strong links. This will help researchers visualize how these stations continue to supply electric power to consumers without interruption. This is done through the internal treatment of the station or the strengthening of the links between stations. As well as, this work will also give an impression of the weak stations whose connections must be strengthened in order to make them effective stations.

In future work, from the study of the above-mentioned properties, theories will be developed to address the weakness of the *IPG* network. This is done by presenting strategies (Scenarios) and proposals to improve the *IPG* network performance in all aspects. For instance, these Scenarios will be used to treat out-of-service units and stations to enhance the performance of the network. As well as, establishing new power stations and their connection lines, performing network characteristics calculations, and comparing them with the current *IPG* network.

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Authors' Declaration:

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Besides, the Figures and images, which are not ours, have been given permission for re-publication attached with the manuscript.
- The author has signed an animal welfare statement.
- Ethical Clearance: The project was approved by the local ethical committee at the University of Mosul.

Authors' Contributions Statement:

MY and RJ conceived of the presented idea. RJ collected the dataset as well as modeled, analyzed, and developed the theory. RJ performed the computations and verified the analytical methods. MY encouraged RJ and supervised the findings of this work. RJ and MY discussed the results, revision, proofreading, drafted the MS and contributed to the final manuscript.

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نمذجة شبكة الكهرباء في العراق

رشا جمال الجراح **منار يونس كشمولة**

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الخلاصة:

في الآونة الأخيرة ، أخذت نظرية الشبكات المعقدة (Complex Networks) إتجاه حديث وفعال بدخولها ضمن مجموعة متنوعة من التطبيقات في حياتنا. حيث تستخدم نظرية الشبكات المعقدة في تشكيل الظواهر المعقدة في النماذج القائمة على الرسم البياني التي تتألف من العقد بالإضافة الى الحواف التي تربطها. يمكن تقييم وتحليل هذا التمثيل بإستخدام مقاييس الشبكة مثل درجة العقدة ، معامل التجميع ، طول المسار ، المركزية، القرب، البينية ، الكثافة ، والقطر، على سبيل المثال لا الحصر. تعتبر طوبولوجيا الترابطات المعقدة لشبكات الطاقة أحد المشاكل التي ممكن مواجهتها من ناحية فهم الشبكة أو تحليلها. لذلك ، تستخدم بعض البلدان حول العالم مفاهيم الشبكات المعقدة لنمذجة وتحليل شبكات الطاقة الخاصة بها. في هذا العمل ، تم نمذجة وتصور شبكة الكهرباء الوطنية العراقية (*IPG*) وتحليلها وفق نظرية الشبكات المعقدة من خلال تمثيل المحطات كعقد وخطوط نقل الكهرباء بين المحطات كحواف. هذا التحليل يتم من خلال تطبيق مقاييس خصائص الشبكة على شبكة *IPG* الوطنية المقترحة. أخيرا، يوفر هذا العمل تصورًا احترافيًا للشبكة التي تم إنشاؤها بناءً على التوزيع الديموغرافي وإحداثيات محطات الطاقة. وبالتالي فأن الشبكة المقترحة مفيدة لوزارة الكهرباء العراقية والتي ممكن أن يتبناها المسؤولون والمختصون من أجل فهم وتصور وتقييم أداء شبكة *IPG* الحالية من منظور مختلف لأنها لا تزال قيد التطوير والتحديث.

الكلمات المفتاحية: الشبكات المعقدة، مقاييس الشبكة، نموذج الشبكة، شبكات الطاقة.