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Design of an Electrical Network for the West Bank of Palestine with the Selection of Optimum Site of the Generating Power Plant

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Abstract: The aim of this study was to design an electrical network for the West Bank of Palestine selecting the optimum site of the generating power plant. The required network should have the optimum configuration and realize the technical and economical requirements. It should provide the consumer with electric energy of high quality, reduce the cost of electric energy supplied to consumer and have the minimum possible total annual cost.

Key words: Optimum configuration, technical and economical comparison, load flow

INTRODUCTION

Energy sector in Palestine since the Israeli occupation faced severe technical, financial and management obstacles due to the severe restrictions imposed by the Israeli occupation. As a result of this situation Palestine has not yet a unified power system, the existing networks are local low voltage distribution networks connected to Israeli Electric Corporation (IEC) where, around 97% of the consumed energy were and still supplied by the IEC. The voltages of the existing distribution networks are 0.4, 6.6, 11, 22 and 33 KV. IEC supplies electricity to the electrified communities by 22 or 33 KV by overhead lines. Electricity is purchased from IEC and then distributed to the consumers. The existing electricity situation is characterized in old fashion over loaded networks, high power losses (more than 20%), low power factor, poor system reliability, high prices of electricity supplied to customer due to high tariff determined by the IEC, in addition many villages depend on diesel generators to provide their own needs of electrical energy. Due to all factors mentioned above it becomes very important to design a national independent power system for the West Bank of Palestine which will connect all the West Bank areas by a reliable network to a national generating plant. The national power system should have the minimum annual cost and provide the consumer with a high quality of electric energy. This power system should also reduce the cost of kilowatt-hour and be able to provide electricity to any area in the West Bank.

PRIMARY DESIGN OF THE NETWORK

The geographical data required for the design of the network is the distances along the roads between the different districts of the West Bank (Fig. 1). Table 1 includes the required technical data for the design; it is the peak loads at different districts of the West Bank[1].

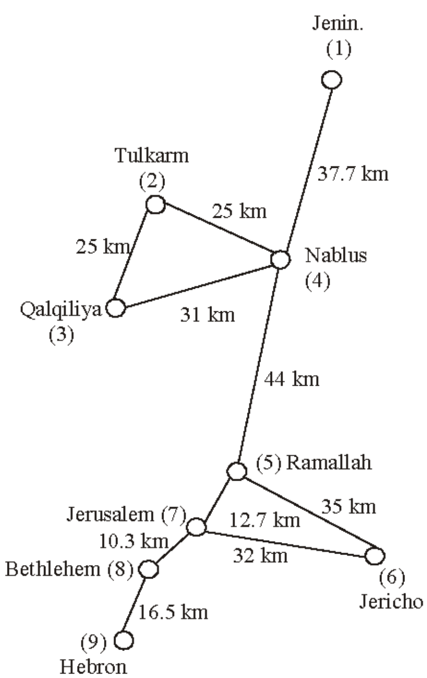

Fig. 1: Distance along the roads between different districts of the West Bank

BALANCE OF REAL POWER

The calculation of the balance of real power is important to determine the estimated real power required from the power plant. Equation 1 guarantees the balance of real power:

$$\sum P_G = \sum P_L + \sum \Delta P_L \quad (1)$$

Where, $\sum P_G$ is the total required real power to be supplied by the power plant in MW, $\sum P_L$ is the total real power consumed by the loads in MW and $\sum \Delta P_L$ are the total real power losses in various branches of the network in MW.

To use Eq. 1 at this primary stage of design when the elements of the network have not been selected yet it is written in the form of Eq. 2 as follows:

$$\sum P_G = 0.9 \sum P_L + 0.075 \sum P_L \quad (2)$$

Where, the factor 0.9 is the estimated demand factor of the loads and the factor 0.075 is used for the primary estimation of the real power losses to be 7.5% of the total load.

Applying Eq. 2 to the data given in Table 1 yields that the required generated power is 267.5 MW. To consider future expansion of the loads the required generated power is multiplied by a future expansion factor of 1.2 to become 320 MW which is the required real power to be generated to the network by the power plant.

Table 1: Peak loads at different districts of the West Bank

District	Peak apparent power S_{MAX} (MVA)	Power factor	Peak real power P_{MAX} (MW)	Peak reactive Power Q_{MAX} (MVAR)
Jenin	29.00	0. 81	23.5	17.00
Tulkarm	17.31	0.78	13.5	10.84
Qalqiliya	12.50	0.80	10.0	7.50
Nablus	49.41	0.85	42.0	26.03
Ramallah	69.76	0.86	60.0	35.60
Jericho	8.00	0.87	7.5	3.96
Jerusalem	50.86	0.88	45.0	23.70
Bethlehem	36.20	0.87	31.5	17.85
Hebron	48.9	0.86	42.0	25.00
Total	321.94		274.5	167.50

Table 2: New peak loads after power factor correction at the load buses

Bus No.	Real and reactive power in Fig. 2a P + j Q, (MVA)	Real and reactive power in Fig. 2b P + j Q, (MVA)	Real and reactive power in Fig. 2c P + j Q, (MVA)
1	23.5 + j 08.10	23.5 + j 08.10	23.5 + j 08.10
2	13.5 + j 04.84	13.5 + j 04.84	13.5 + j 04.84
3	10.0 + j 01.50	10.0 + j 03.60	10.0 + j 03.60
4	42.0 + j 14.03	42.0 + j 17.07	42.0 + j 14.03
5	60.0 + j 17.60	60.0 + j 26.70	60.0 + j 23.70
6	7.0 + j 01.06	7.0 + j 03.96	7.0 + j 01.06
7	45.0 + j 14.80	45.0 + j 17.70	45.0 +j 17.70
8	31.5 + j 11.85	31.5 + j 11.85	31.5 + j 11.85
9	42.0 + j 13.00	42.0 + j 19.00	42.0 + j 16.10

BALANCE OF REACTIVE POWER

The purpose of the calculation of the balance of reactive power is to distribute reactive power sources in the network (mainly capacitor banks) in parallel with the loads to reduce the reactive power generated by the power station. This will reduce the reactive power flow and the currents flowing in the network. Reducing these currents will reduce the cross-sectional areas of transmission lines and the ratings of different machines and equipment and that will save great expenses.

The power plant is suggested to operate at an economical power factor of 0.9 lagging, generating a reactive power of 155 MVAR.

To get the total required reactive power to be generated by capacitor banks, balance of reactive power is calculated according to Eq. 3 as follows:

$$Q_A + \sum Q_{T.L} + \sum Q_C = \sum Q_L + \sum \Delta Q_{T.L} + \sum \Delta Q_{T.R} \quad (3)$$

Where, Q_A is the reactive power delivered by the power plant in MVAR, $\sum Q_{T.L}$ is the total reactive power generated by transmission lines in MVAR, $\sum Q_C$ is the total reactive power generated by capacitor banks in MVAR, $\sum Q_L$ is the total reactive power consumed by the loads in MVAR, $\sum \Delta Q_{T.L}$ are the total reactive power losses in the transmission lines in MVAR and $\sum \Delta Q_{T.R}$ are the total reactive power losses in the transformers in MVAR.

In order to realize the balance of reactive power according to Eq. 3 three primary configurations with different sites of the power plant are suggested. The real power flow in each branch is calculated at this stage without considering real power losses. Real power losses will be taken into account in the final stage of design of the network when the transmission lines and transformers will be selected. A selection of standard voltages for various transmission lines of the three suggested networks is performed as given by Eq. 4[2]:

$$V = \frac{1000}{\sqrt{500/L + 2500/P}} \quad (4)$$

Where, L denotes the length of the line in km, P denotes the real power transmitted by the line in MW and V denotes the calculated voltage in KV.

The calculated voltages by Eq. 4 are estimated to the nearest standard voltages which are: 0.4, 6.6, 11, 22, 33, 66, 132 and 230 KV. The suggested three configurations with the results of the selected standard voltages are shown in Fig. 2.

At this primary stage of design when the transmission lines are not selected yet, the total reactive power generated by transmission lines ($\sum Q_{T.L}$) is considered to be equal to the total reactive power losses in the lines ($\sum \Delta Q_{T.L}$) which is correct for transmission lines operating at nominal voltages not exceeding 230 KV and hence these two components cancel each other.

The total reactive power losses in the transformers are estimated by Eq. 5:

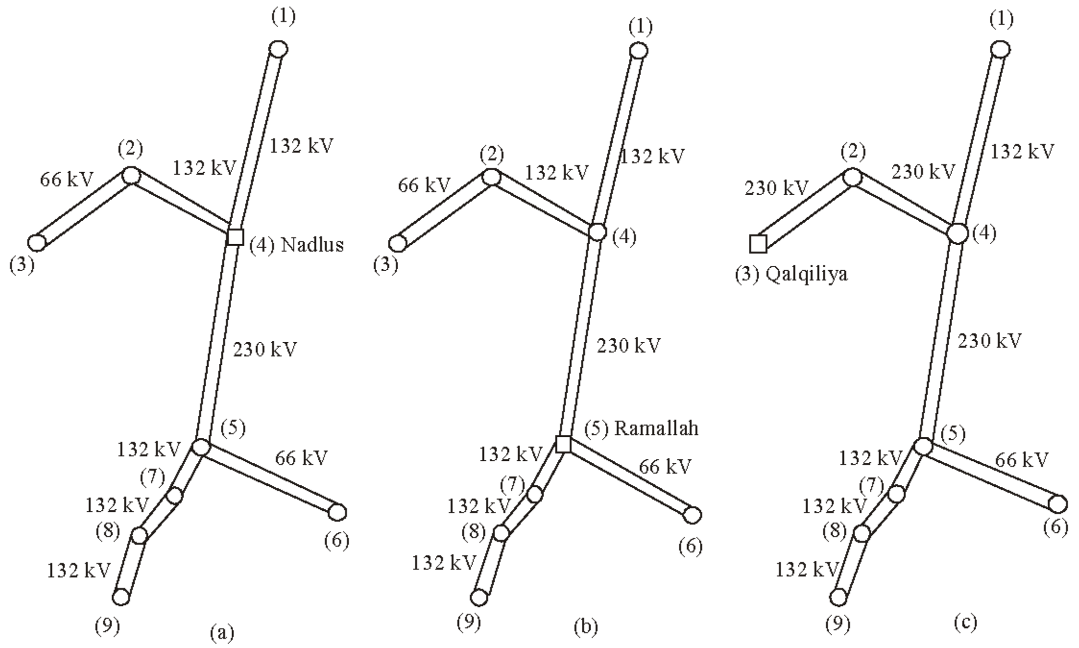

Fig. 2: Primary suggested configurations of the network, where the power plant is in: (a) Nablus (b) Ramallah (c) Qalqiliya

$$\sum \Delta Q_{T.R} = \sum 0.1 * M_i * S_i \qquad (5)$$

Where, S_i is the apparent power load at each bus, M_i is the number of transformation stages for each apparent power load and 0.1 is a percent value to estimate the reactive power losses in transformers[2].

Using a demand factor of 0.9 and considering the above mentioned aspects, Eq. 4 is written in the form of Eq. 6 to find the total reactive power generated by capacitor banks:

$$\sum Q_C = 0.9 \sum Q_L + \sum \Delta Q_{T.R} - Q_A \qquad (6)$$

The total economical reactive power received by the loads from the network is determined by Eq. 7:

$$\sum Q_{econ} = \sum Q_L - \sum Q_C \qquad (7)$$

A new economical power factor at the load buses is calculated by Eq. 8:

$$P.f_{econ} = \cos(\tan^{-1} \frac{\sum Q_{econ}}{\sum P_L}) \qquad (8)$$

The calculated economical power factor of the loads ($P.f_{econ}$) for the three suggested networks is equal to: 0.94 for the network of Fig. 2a, 0.91 for the network of Fig. 2b and 0.92 for the network of Fig. 2c.

Using the economical power factor, new reactive power demand at each bus is determined by Eq. 9:

$$Qi_{new} = Pi * \tan(\cos^{-1} P.f_{econ}) \qquad (9)$$

The difference between the old and new reactive power demand at a bus is the required value of reactive power of capacitor banks to be installed at this bus. The calculated values of capacitor banks reactive power at each bus are estimated to the nearest standard values available in the market. Finally the selected standard values of reactive power of capacitor banks are used to calculate the final new values of reactive power demand at each bus.

The results of new load demands at each load bus calculated for the three suggested networks are listed in Table 2. These load demands calculated according to the economical power factor will be the new load demands at the buses that will be considered in the next stages of this study.

SELECTION OF THE OPTIMUM CONFIGURATION OF THE ELECTRICAL NETWORK

Different configurations are suggested for the network. In designing these configurations the following factors are considered:

- The power should be transmitted from the power plant to the loads by the minimum possible distances, keeping the direction of power flow to be from the power plant to the loads without return paths of power transmission.

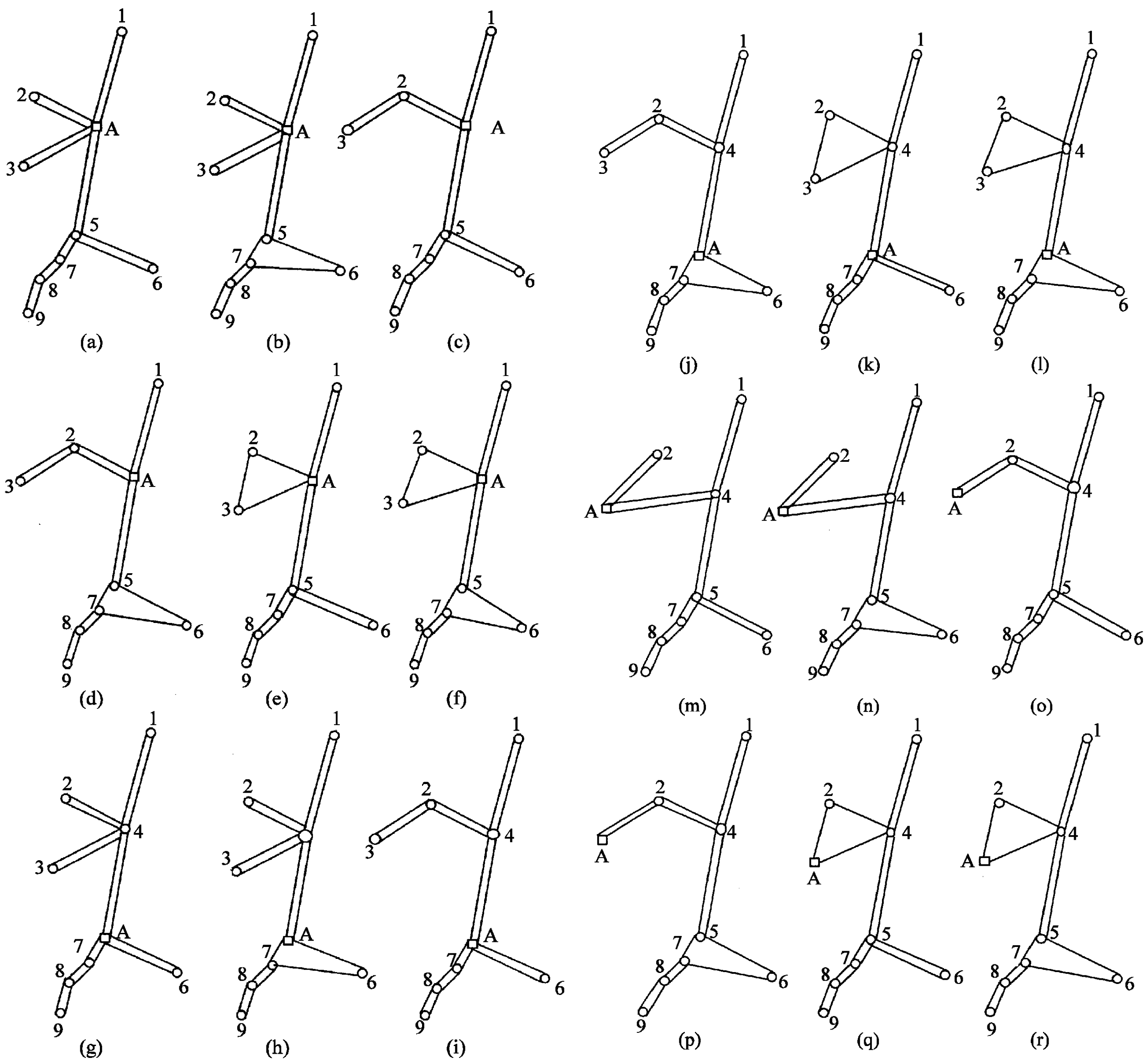

Fig. 3: Suggested configurations of the network with the site of the power plant A is in, a) Nablus Fig. 3a-f, b) Ramallah Fig. 3g-l, c) Qalqiliya Fig. 3m-r

- Radial, ring and compounded configurations are to be considered. Radial lines are double lines to ensure reliability of the network, but they have more total length of transmission lines than ring designs, while ring designs include substations with higher capital cost than radial designs.
- Several sites of the generating power plant are to be considered. In several proposals different sites were suggested to be the site of the power plant; one of these proposals was to have the site in Ramallah[3], another proposal was to have the site in the north of the West Bank in the city of Qalqiliya[4], but these proposals did not take into account the optimum design of the overall network when suggesting the site of the power plant.

Taking into account the above mentioned factors, several configurations with different sites of the power plant are suggested for the network. Three cities are suggested for the site of the power plant. These cities are: Nablus, Ramallah and Qalqiliya. The suggested configurations are represented in Fig. 3. These configurations will be compared with each other to select the optimum one.

PRIMARY CHOICE OF THE NETWORKS CONFIGURATIONS

The purpose of this study is to reduce the number of the suggested configurations to the minimum number taking into account the following factors: the minimum total length of transmission lines and the minimum total number of three-winding transformers used in each network. This comparison study starts with the calculation of power flow in each network neglecting losses. Losses will be considered later in the final technical and economical comparison study when transmission lines and transformers will be selected. The next step is to select the line voltages for each transmission line according to Eq. 4. An important factor that should be considered in the selection of the voltages is that the required electrical network should be of 2-3 nominal voltages. This is important in order to reduce the number of substations that connect transmission lines of different voltages. These substations with three-winding transformers or autotransformers are very expensive elements of the network.

The calculated voltages are estimated to the nearest standard values and then used to find the total number of three-winding transformers in each network. The results of this primary study that include the total distance, the total length of transmission lines and the total number of three-winding transformers in each network are listed in Table 3.

Considering the above mentioned factors, obtained results in Table 3 are analysed in order to reduce the number of the configurations to minimum value for the next study. Six configurations are selected. The selected configurations have different shape and different site of the power plant which is suggested to be in Nablus for the networks in Fig. 3a and f; in Ramallah for the networks in Fig. 3g and b and in Qalqiliya for the networks in Fig. 3o and 3r.

TECHNICAL AND ECONOMICAL COMPARISON

The six previously selected configurations are subjected to accurate technical and economical comparison study to select the optimum one. In this more precise study several elements are selected for each design including transformers, transmission lines and switchgears taking into account the technical aspects for the selections. The next step is to calculate the total annual cost for each design in order to select the optimum configuration with the minimum total annual cost.

Two transformers are selected at each bus to ensure reliable power supply in the case of maintenance or fault

Table 3: Results of the primary comparison study between the suggested configurations of the network

Configuration Fig. No.	Total length of lines, L (KM)	Total distance, D (KM)	Taotal No. of three-winding transformers
3a	424.4	212.2	1
3b	408.7	244.2	1
3c	412.4	206.2	2
3d	396.7	238.2	2
3e	393.4	237.2	1
3f	377.7	269.2	1
3g	424.4	212.2	1
3h	408.7	244.2	1
3i	412.4	206.2	2
3j	396.7	238.2	2
3k	393.4	237.2	1
3l	377.7	269.2	1
3m	424.4	212.2	2
3n	408.7	244.2	2
3o	412.4	206.2	2
3p	396.7	238.2	2
3q	393.4	237.2	2
3r	377.7	269.2	2

at one of them. The rated power of each transformer at a bus is selected by Eq. 10 as follows:

$$S_{T_{rated}} > \frac{S_{load}}{1.4} \quad (10)$$

Where, $S_{T\ rated}$ is the rated apparent power of each transformer at a bus in MVA and S_{load} is the apparent power load at the bus in MVA.

Selection of transmission lines is performed considering that the cross-sectional areas of the conductors should be able to carry the maximum normal current during normal operation of the network and maximum currents that flow after a fault had occurred and some parts of the network are disconnected to clear the fault. The selected cross-sectional area should realize economical considerations and be suitable to reduce real power losses in the lines.

The economical cross-sectional area can be found by Eq. 11[2]:

$$F_{economical} = \frac{I_{normal}}{J} \quad (11)$$

Where, F economical is the calculated economical cross-sectional area of the conductor in mm^2, I_{normal} is the maximum current flowing in the line during normal operation in A and J is the economical current density selected as 1.4 A mm^{-2}[2].

The achieved value of F economical is estimated to the nearest greater standard cross-sectional area.

The selection of switchgears for each suggested configuration is done taking into account several factors as: nominal voltage, number of transmission lines connected to the switchgear and other factors related to the working conditions of the substation for which the switchgear is selected.

According to the technical aspects mentioned above selection is done for transformers, transmission lines and switchgears for each one of the six suggested configurations.

The six suggested configurations are compared with each other economically to select the optimum one with the minimum total annual cost. The total annual cost for each configuration is calculated according to Eq. 12[2]:

$$Z = E_n * K + I \quad (12)$$

Where, Z denotes the total annual cost in \$/year, E_n denotes the capital recovery factor taken as $E_n = 0.12$ in 1/year[2], K denotes the total capital cost of transmission lines and substations including transformers and switchgears in \$ and I denotes the total running cost of transmission lines, substations and energy losses in \$/year.

Since the aim of this study is to compare between the suggested configurations to select the optimum one with the minimum total annual cost, the calculation of the total annual cost considers the elements of the networks which are different from one network to another but neglects other identical elements.

The total capital cost of transmission lines is calculated taking into account the length of transmission lines, cross sectional area, operating voltage and number of transmission lines in parallel.

The total capital cost of transformers depends upon the rated power of the transformers, the rated voltages and the types of the transformers (two-winding, three-winding, or autotransformers).

The total capital cost of switchgears is calculated taking into account the type of the switchgear, the operating voltage and number of circuit breakers used in the switchgear.

The total transmission line's running cost is calculated as a percentage of the total capital cost of transmission lines taking into account the towers material and the operating voltage of the line. This percent value is selected as 2.8%[5].

The total substation's running cost is calculated as a percentage of the total capital cost of substations taking into account the operating high voltage of the substation. This percent value is selected as 8.8% for substations with a high voltage up to 132 KV and 7.8% for substations with a high voltage of 230 KV[5].

Energy losses' running cost is calculated according to Eq. 13[5]:

$$I_{\Delta W} = Z1 * (\Delta W1 + \Delta W2) \quad (13)$$

Where, $I_{\Delta W}$ is the energy losses' running cost in \$/year, $\Delta W1$ are the variable energy losses in transmission lines and copper losses in transformers in MWh, $\Delta W2$ are the constant energy losses which are the core losses in transformers in MWh and Z1 is the energy price. In the West Bank Z1 is 140 \$/MWh

Table 4: Total annual cost of each of the six suggested configurations

Configuration Fig. No.	Total capital cost K (\$)	Total running cost I (\$/year)	Total annual cost Z (\$/year)
3a	15973980	4473894.24	6390771.84
3f	16918210	4770872.28	6801057.48
3g	15903980	3813800.64	5722278.24
3l	16848210	4119629.08	6141414.28
3o	18866580	5944819.84	8208809.44
3r	19279410	6559248.28	8872777.48

The obtained values of the total annual costs calculated by Eq. 12 for each one of the six suggested networks are shown in Table 4.

Table 4 shows that configuration represented in Fig. 3g has the lower value of the total annual cost and so it is selected as the optimum configuration for the network of the West Bank.

In the selected optimum configuration the suggested site of the power plant is the city of Ramallah. This achieved result agrees with the fact that Ramallah is not far from Gaza port in comparison with the other two cities: Nablus and Qalqiliya and this is an important factor for fuel transport that is expected to come by sea tanker to Gaza port then by road tankers to the West Bank. Adding to that Ramallah now is the center of the Palestinian National Authority which makes it easy to construct the power station there and it has good access for the delivery of materials and equipment during construction, also for delivery of spare parts and for supplying maintenance. In addition to the above mentioned factors it is convenient to install the new generation capacity of the West Bank up to year 2020 in one place in order to minimize operation, maintenance and logistic costs.

LOAD FLOW STUDIES

The selected optimum network will be subjected to load flow studies to check its performance and to determine the measures and techniques needed to improve it. These studies are done for the following four cases of the network's operation:

- Peak load condition when loads are at their peak values.
- Minimum load condition when loads are at their lower values.
- Post-fault condition when a fault had occurred and some parts of the network are disconnected.
- Future forecasted load condition.

The impedance diagram of the selected network is drawn and the above mentioned calculations are

Table 5: The results of real power losses and power generation for several conditions of the selected network

Condition	Real power losses (Original case) ΔP, (MW)	Real power losses (Improved case) ΔP, (MW)	Power generatoin (Original case) P_G, (MW)	Power generation (Improved case) P_G, (MW)
Peak load	4.111 (1.47%)	2.993 (1.07%)	279.111	277.993
Minimum load	0.513 (0.46%)	0.513 (0.46%)	110.713	110.713
Post-fault on (A-4)	3.525 (1.27%)	---	278.525	---
Post-fault on (A-7)	3.822 (1.37%)	---	278.822	---
Forecasted load (Year 2015)	13.407 (2.84%)	7.989 (1.71%)	472.007	466.589

performed by using a computer program of load flow to get the voltages at each bus, the power and reactive power flow in each branch, the total real and reactive power losses and the total real and reactive power generation in each case.

The obtained results of load flow for the peak load condition show that the voltages at some buses are not acceptable being below the nominal values. The aim of improvement in this case is to increase the voltages at each bus to become above the nominal values not exceeding 10% above the nominal values. This is necessary to reduce the additional voltage drop and power losses in the low tension distribution networks. This goal was achieved by increasing the swing bus voltage at Ramallah by 10% and regulating the turn's ratio of some of the Tap Changing Under Load (TCUL) transformers.

Since Palestine is not an industrial country where factories and industrial plants do not work at night, the minimum load condition is important for study. By studying the load curves of different districts of the West Bank the minimum load is estimated to be 40% of the peak load. Calculating the power flow of the network in the minimum load condition shows that it is enough to regulate the turn's ratio of some of the TCUL transformers to keep the voltages to be close to the nominal values and that is the required and accepted condition in this case when the conductors and transformers are operating at light load.

The post-fault condition is studied in two cases: first when one line of the double line A-4 is disconnected and the other is when one line of the double line A-7 is disconnected to clear assumed faults. These two lines are selected to represent the post-fault conditions since they are the lines of the maximum power flow in the network and disconnecting one of the two parallel lines in each case represents the most difficult post-fault case. Analysing the results obtained in these two cases, it is seen that the voltages at all the buses are still above the nominal values and that the real power losses are of reasonable values.

The load in any electrical network is subjected to a normal growth that must be taken into account when designing the network. This growth is influenced by many factors including the demographic growth, the local economy, energy prices and energy conservation. The uncertain growth factor is estimated to be 67% up to the year 2015[6].

The load flow study is performed for the network with the loads as estimated to be in the year 2015 at the peak load condition. The obtained results show that the voltages at some buses become lower than the acceptable values. In order to improve the network's performance at this condition it becomes necessary in addition to regulating the swing bus voltage and the TCUL transformers, to install some capacitor banks in parallel with the load buses that have the lowest values of voltages. The payback period of these capacitors is calculated to be four months. The obtained results of the improved case show that the real power losses have been decreased and that the voltages become in an acceptable range above the nominal values.

The results of the above calculations for the four mentioned conditions are shown in Table 5 including real power losses and real power generation in the original and the improved cases.

Figure 4 shows the one-line diagram of the selected network with the results of the improved peak load condition. These results include the power and reactive power flow in each branch and the voltages at each bus.

More detailed results including the voltages at each bus for all the four conditions of the selected network are listed in Table 6.

Analysing the obtained results of load flow studies for different conditions of the network's performance shows that using some simple measures as increasing the swing bus voltage and regulating the turn's ratio of some of the TCUL transformers was enough to improve the performance of the network reducing the real power losses and increasing the voltages to acceptable values. This is very important to supply the consumer with electric energy of high quality and decrease the cost of the provided energy.

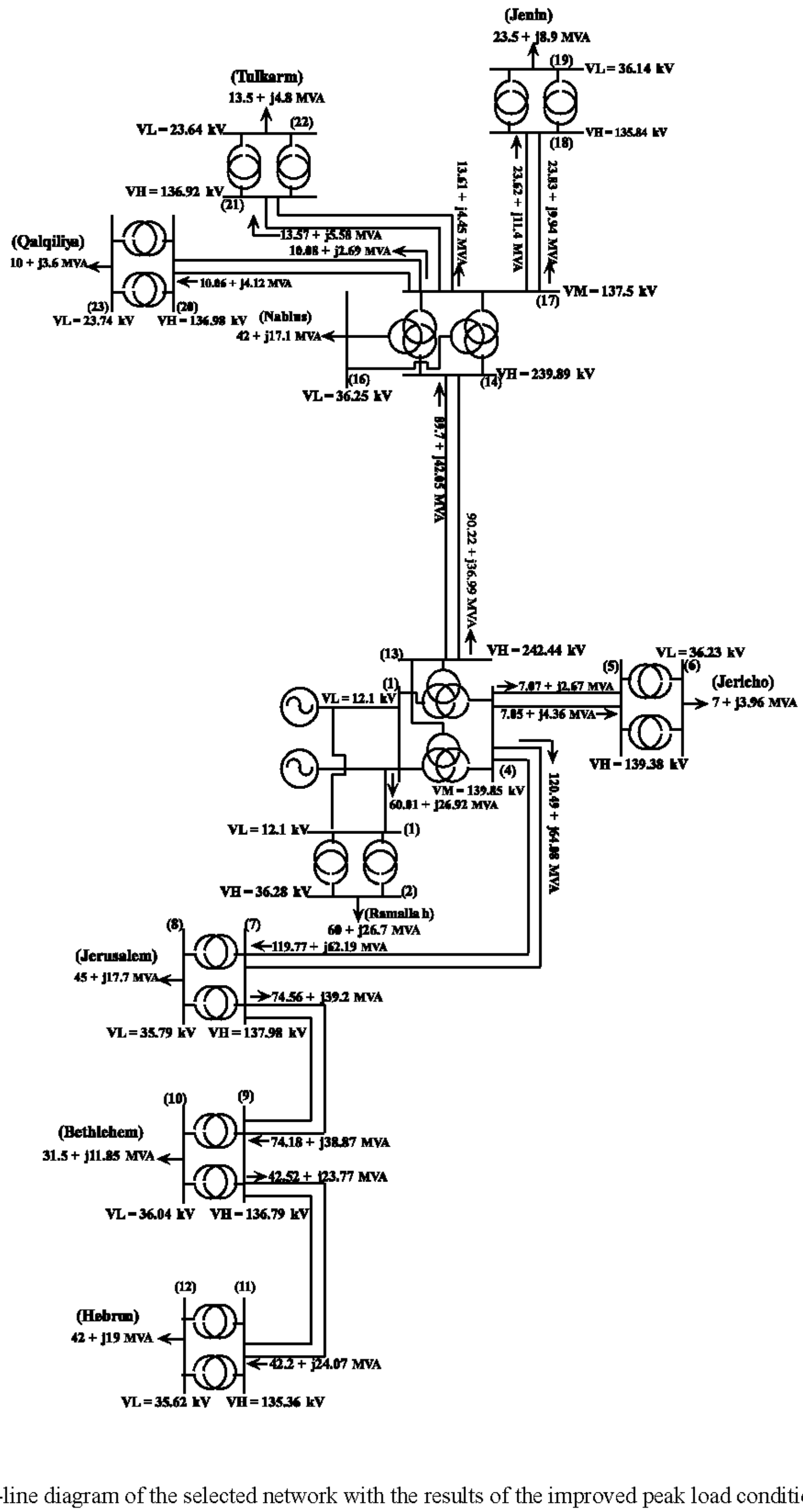

Fig. 4: The one-line diagram of the selected network with the results of the improved peak load condition

Table 6: The results of the voltages at each bus for several conditions of the selected network

Bus No.	Voltage (KV) peak load improved case	Voltage (KV) min. load improved case	Voltage (KV) post-fault on line (A-4)	Voltage (KV) post-fault on line (A-7)	Voltage (KV) year 2015 improved case
1	12.10	11.00	12.10	12.10	12.10
2	36.28	33.01	36.28	36.28	36.24
3	11.47	10.81	11.43	11.45	10.84
4	139.85	130.27	139.41	139.59	144.56
5	139.38	130.09	138.94	139.12	143.77
6	36.23	34.00	36.12	36.16	36.09
7	137.98	129.54	137.54	135.73	141.59
8	35.79	33.44	35.66	35.15	36.19
9	136.79	129.07	136.34	134.52	139.76
10	36.04	33.30	35.91	35.38	35.96
11	135.36	128.49	134.90	133.05	137.63
12	35.62	33.13	35.49	34.95	35.94
13	242.44	228.40	241.69	242.00	252.12
14	239.89	227.56	236.27	239.43	247.66
15	234.89	225.93	231.14	234.42	239.07
16	36.25	33.79	35.64	36.17	36.19
17	137.50	129.67	135.31	137.23	146.12
18	135.84	129.01	133.61	135.56	143.36
19	36.14	33.41	35.50	36.06	36.01
20	136.98	129.46	134.77	136.70	145.28
21	136.92	129.43	134.71	136.64	145.18
22	23.64	22.52	23.25	23.59	24.00
23	23.74	22.56	23.35	23.69	24.15

* Bus numbers are given according to Fig. 4

CONCLUSIONS

Different configurations of the electrical network of the West Bank with different sites of the power plant are suggested and compared with each other to select the optimum one. The optimum network with the minimum total annual cost, minimum power losses, lowest voltage drops and higher reliability was selected. The optimum site of the generating power plant is recommended to be in Ramallah. The selected network was subjected to load flow studies to check its performance in several conditions: peak load condition, minimum load condition, post-fault condition and forecasted load condition. The obtained results show that using some simple measures was enough to improve the performance of the selected network reducing the real power losses and improving the voltage level of the network. The selected optimum network which has the minimum total annual cost and provides the consumer with electric energy of high quality is recommended to be the future network of the power system of the West Bank of Palestine.

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