Journal of Engineering and Applied Sciences 13 (8): 2156-2161, 2018
ISSN: 1816-949X

Power Losses Minimization Using on Load Tap Changer Transformers and Injected Reactive Power

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Abstract: This study investigates the influence of main voltage control methods to minimize active power losses in the practically studied power system. An understanding of the power system losses is important not only to the power system engineer but also to the policy maker. The study focuses on improving the operating performance of electrical power system by reducing the power losses and improving the power quality. Control of the transformation ratio of power transformers and reactive power injection has been used to optimize the performance of the Jordanian electric system. The simulations have been implemented in MATLAB. Optimal transformation ratios and injected reactive power are determined for different actual operating modes (maximum, average and minimum load) for the Jordanian electric power system. Power losses versus the controlling variables are illustrated. Recommendations for optimal control variables of main substations are obtained, taking into account the limits of process control optimization.

Key words: Voltage control, tap changer, power losses, substation, transformation ratio, reactive power

INTRODUCTION

The Jordanian power system network, like all other power systems, waves about the entire country and it is interconnected with Syria and Egypt (NEPCO, 2015) No. matter how carefully the system is designed, losses are present. Electric power losses are wasteful energy caused by external factors or internal factors and dissipated in the system (Penny and Lindfield, 1995; Al-Thaimer, 2001; Abdallah and Al-Thaimer, 2003). The problem of minimizing energy losses in electric networks is an important aspect of energy systems research. There are many methods used to improve the performance of the electrical system for optimum operation modes that satisfy the voltage quality and reliability of the electrical system. Energy losses are affected by the automatic voltage control of power transformers and control of injected reactive power (Liu *et al*., 2002, Sarimuthu *et al*., 2016). On load tap changer transformers and shunt capacitors are used to minimize power losses and maintain the profile of the voltage in the permissible values at the consumer terminals. As consumer loads of electric power system are variable with time, the optimal operation mode may be possible by controlling the means of regulating devices. Minimizing power losses is the main criterion of this study. The calculations for determining optimal transformation ratios and injected optimal reactive power are performed for different actual operating modes [maximum, minimum and normal load], Digsilent program is used to evaluate the influence of the controlling variables on the performance of the power system. The results of each case study are introduced in the tables, they include: the active power losses, reactive power losses and the voltage drop at the terminals. Many mathematical models are studied to estimate power losses using the transformation ratio (and/or) injected reactive power using MATLAB.

Equations reflect the relationships of power losses as a function of the transformation ratio (and/or) injected reactive power are obtained. The curves of the power losses versus the controlling variables have been illustrated. Optimal controlling variables for main substations are introduced. In this study, new substations (Qatrana and Amman North) are studied, to measure the expected effect of adding these substations to the Jordanian electrical power system. According to the results obtained, recommendations for improving the performance of the power system are introduced. The regulation limits of the optimization process are taken into consideration to be not exceeded. The power losses in electrical network as well as real and reactive power flows for all equipment connecting the buses can be computed by means of load flow simulation. The quantification and minimization of losses are important because it will

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determine the economic operation of the power system (Lukman and Blackburn, 2003). If we know how the overall losses occur, we can take steps to minimize them. Active power losses can be determined by various methods. The power losses can be calculated by the equation (Al-Thaimer, 2001):

$$\Delta P = \sum_{i=1}^{n} R_i \left(I_{ia}^2 + I_{ir}^2 \right) \qquad (1)$$

With the following constraints:

$$MI_a = J_a,\ MI_r = J_r,\ (I_{ia}^2 + I_{ir}^2)^{1/2} \le I_{i.per},\ J_{ia\min} \le J_{ia} \le J_{ia\max},\ J_{ia\min} \le J_{ia} \le J_{ia\max}$$

Where:

M = The first incidence matrix
R = Branch resistances
I = Branch currents
J = Nodal currents
$_a$ = Active component of the current
$_r$ = Reactive component of the current
$_I$ = Branch index
$_n$ = Number of branches

To obtain the relationship between the losses and the transformation ratio $\Delta P_* = f(K_*)$ different numerical analysis methods are used to define the final formula:

$$\Delta P_* = aK_*^{\alpha} + bK_*^{\beta} \qquad (2)$$

Where:

$$\Delta P_* = \frac{\Delta P}{\Delta P_0},\ K_* = \frac{K}{K_0} \qquad (3)$$

The a, b, α, β are constants that reflect the influences of the transformation ratio on the operating mode (Abdallah and Al-Thaimer, 2003). The power losses in a line can also be calculated by taking the algebraic sum of the total power flows in either direction and the total losses would be the sum of all the line losses (Weedy, 1979). Two methods to reduce the power losses on the system network which will be discussed in this study include:

- The change of transformer taps settings
- Addition of different values of capacitor banks to control reactive power distribution

MATERIALS AND METHODS

Application of tap changers of transformers: Tap changing can control the reactive power flow, so, optimum bus voltages can be determined and reduce the losses. A method of controlling the voltages in a network makes the use of transformers, the turns ratio of which may be changed (Sarimuthu *et al*., 2016; Liang *et al*., 2011). A schematic diagram of an off-load tap changer is shown in Fig. 1a which requires disconnection of the transformer when the tap setting is to be changed. Many transformers now have on-load tap changers as can be shown in Fig. 1b. The presence of a tap changer allows manual or automatic change of the turn ratio and hence, of the output voltage. Because of the impedance of the lines, the voltage at the receiving end is slightly lower than the voltage at the sending end for most loads. In order to get a constant and rated voltage at the secondary of a 'normally' step-down transformer automatically, an on load tap changer with additional S1 and S2 transfer switches and R center-tapped reactor is mounted on the primary side of it as shown in Fig. 1b.

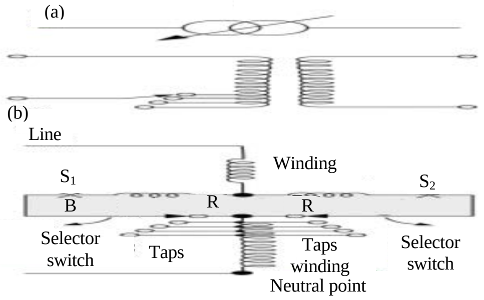

Fig. 1: a) Off-load tap changing transformer and b) On-load tap-changing transformer with S1 and S2 transfer switches, T center-tapped reactor

Assume that an automatic load tap changing transformer (OLTC) is connected to a particular bus to keep load voltage constant. It is possible to run the load flow program employing one tap setting and without mentioning the magnitude of load voltage. If the voltage magnitude determined by the load flow program run exceeds the given limits, a new tap setting is then selected for the next run. In general, when the automatic tap changing feature is employed to represent a manual tap-changing transformer, the output of the load flow program will specify the tap setting that gives the required bus voltage.

The change of tap setting or turn ratio will change the system impedance matrix. Therefore, after each tap ratio adjustment, the Y bus admittance matrix has to be adjusted. Another means of taking into account the OLTC transformer is to represent it by its impedance or admittance, connected in series with an ideal autotransformer as shown in Fig. 2a. A model of a load taps changer needs to be developed. An equivalent

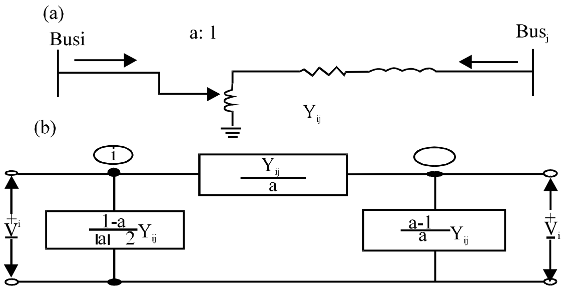

Fig. 2: OLTC transformer representations: a) Equivalent circuit and b) Equivalent circuit

circuit as shown in Fig. 2b (Gonen, 1988) can be developed in load flow studies. The presence of the tap changing transformer causes necessary modifications to the Newton Raphson power flow technique. The elements of the equivalent circuit can then be treated in the same manner as line elements.

The following parameters of the equivalent circuit (Fig. 2b) in terms of admittances and off nominal turn's ratio T can be derived (Lukman and Blackburn, 2003):

$$A = \frac{y_{ij}}{T};\ B = \left(1 - \frac{1}{T}\right)y_{ij};\ C = \frac{1}{T}\left(\frac{1}{T} - 1\right)y_{ij} \tag{3}$$

T = Per unit turns ratio. The presence of a tap changing transformer changes the elements of both diagonal and off-diagonal of the bus admittance matrix where the transformer is connected between two buses.

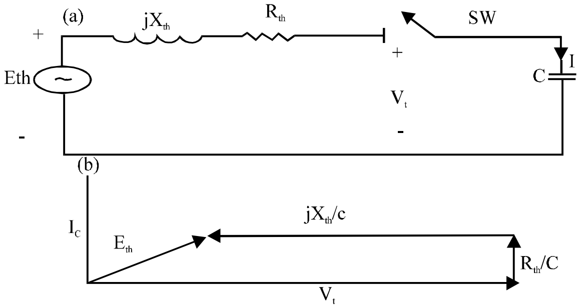

Fig. 3: Effect of adding a shunt capacitor to a power system bus

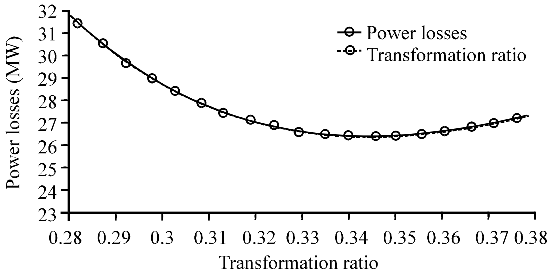

Fig. 4: Power loss reduction using automatic tap changing

Application of switched capacitor banks: Capacitors are used in the transmission/distribution line to increase line load ability (maximum power transfer) and to adjust the system voltage (Lukman and Blackburn, 2003). Shunt capacitors are used to deliver reactive power and increase the voltage magnitudes during heavy load conditions. Figure 3 shows the effect of adding a shunt capacitor bank to a power system bus. The system is represented by its Thevenin equivalent at the node where the capacitor will be applied by closing the switch. With the switch open, the node voltage Vt is equal to the Thevenin voltage Eth. From the power flow standpoint, the addition of a shunt capacitor bank to a load bus corresponds to the addition of a negative reactive load. The power flow program computes the increase in bus voltage magnitude along with the small change in phase angle. The additional capacitor is modeled with the susceptance (B). Given a required reactive power injection of Q, the susceptance (B) can be calculated from Q = V2B. V is the initial voltage of the bus where the shunt capacitor needs to be installed. The addition of capacitor bank changes the bus admittance matrix similar to the change of tap setting of transformer. However, it will only affect the element of the diagonal admittance matrix of the bus where the capacitor is added.

In this study the polynomial functions are implemented for their simplicity in: Definition, roots and graphs. The general form of this function is:

$$f(x) = a_nX^n + a_{n-1}X^{n-1}+, ...,+ a_1X + a_0 \tag{4}$$

The value of n must be a nonnegative integer. The coefficients as they are called are an, an-1, ..., a_1, a_0. These are real numbers. The degree of the polynomial function is the highest value for n where (a) is not equal to 0.

Case study: The substations Al Qatrana and Amman north are studied, to measure the expected effect of adding these substations to the Jordanian electrical power system. To explore the result in this study, we introduce only the data and the calculations for Amman South substation (maximum loading).

Power loss reduction using automatic tap changing (transformation ratio) to obtain the relationship between the active power losses and automatic tap changing (transformation ratio), ΔP = f (KT), MATLAB curve fitting was used according to the real results as shown in Fig. 4. The power losses can be determined by using the polynomial function:

Table 1: Effect of tap changer on active power losses

Tap changer	Transformation ratio	High voltage terminal (kV)	Low voltage terminal (kV)	Active power losses (MW)	Reactive power losses (Mvar)
-9	0.280	439.10	122.33	31.66	-107.49
-8	0.286	426.64	123.92	30.65	-116.52
-7	0.291	434.07	125.44	29.77	-123.86
-6	0.297	431.40	126.19	29.01	-129.62
-5	0.302	428.64	128.29	28.36	-133.93
-4	0.308	425.81	129.63	27.81	-136.90
-3	0.313	422.91	130.91	27.35	-138.61
-2	0.319	419.95	132.13	26.98	-139.15
-1	0.324	416.95	133.30	26.69	-138.61
0	0.330	413.89	134.43	26.47	-137.06
1	0.336	410.81	135.50	26.32	-134.57
2	0.341	407.69	136.52	26.24	-131.19
3	0.347	404.55	137.49	26.22	-127.00
4	0.352	401.38	138.42	26.25	-122.03
5	0.358	398.20	139.31	26.33	-116.34
6	0.363	395.62	140.16	26.46	-109.99
7	0.369	391.82	140.96	26.64	-103.01
8	0.374	388.62	141.73	26.86	-95.44
9	0.379	385.42	142.46	27.11	-87.33

$$Y = a_1X^3 + a_2X^2 + a_3X + a_4 \tag{5}$$

Where:

Y = ΔP-indicates active power losses in MW
X = KT -indicates transformation ratio
a_1 = Coefficient of X3
a_2 = Coefficient of X2
a_3 = Coefficient of X
a_4 = Absolute coefficient

The active power losses as a function of transformation ratio are introduced for each substation as shown in Table 1. Power losses as a function of transformation ratio are given by the following approximated expression:

$$\Delta P = -5072.6K_T^3 + 6198.5K_T^2 - 2466.5K_T + 347.7$$

The optimum transformation ratio for maximum load operation is: KT = 0.3470 and the minimum power losses due to this transformation ratio are: ΔP = 26.22 (MW). Power losses reduction by using shunt capacitors (reactive power control):

To obtain the relationship between the active power losses and the injected reactive power P = f (Q_{inj}). MATLAB curve fitting was used according to the real results as shown in Fig. 5. The power losses are determined by the following expression:

$$Y = A1*X3+A2*X2+A3*X+A4 \tag{6}$$

Where:

Y = Indicates active power losses value in (MW)
X = Indicates reactive power injected in (MVAR)
A1 = Coefficient of X3
A2 = Coefficient of X2
A3 = Coefficient of X
A4 = Absolute coefficient

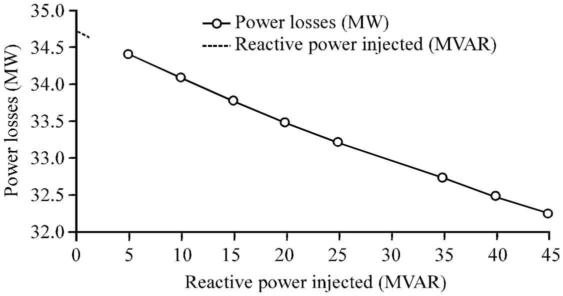

Fig. 5: Power losses reduction by using shunt capacitors

Table 2: Effect of injected reactive power on active power losses

Reactive power injected (Mvar)	High voltage terminal (kV)	Low voltage terminal (kV)	Active power losses (MW)	Reactive power losses (Mvar)
5	407.33	127.06	34.37	-62.14
10	408.97	127.62	34.06	-69.22
15	410.61	128.19	33.77	-76.13
20	412.27	128.78	33.48	-82.88
25	413.93	129.33	33.21	-89.45
35	417.29	130.49	32.71	-102.06
40	418.99	131.07	32.47	-108.09
45	420.69	131.66	32.26	-113.95

The active power losses as a function of injected reactive power are introduced for each substation as shown in Table 2. Power losses as a function of injected reactive power are given by the following approximated expression:

Plosses = 0.0002*Qinjected2-0.0644*Qinjected+34.6865

The optimum injected reactive power for maximum load operation is: Qinjected = 45 (Mvar). The minimum power losses due to optimum injected reactive power are: P_{losses} = 32.26 (MW). Power losses reduction using automatic tap changing transformer (transformation ratio) and shunt capacitors (reactive power control).

Fig. 6: Power losses reduction using automatic tap changing

To obtain the relationship between the active power losses using automatic tap changing transformer (transformation ratio) and injected reactive power P = f (KT, Qinj) , MATLAB curve fitting was used according to the real results as shown in Fig. 6. The power losses are determined by the following expression:

$$Z = A1 * X + A2 * Y + A3 \tag{7}$$

Where:

Z = Indicates active power losses in (MW)
X = Indicates injected reactive power in (MVAR)
Y = Indicates transformation ratios
A1 = Coefficient of X
A2 = Coefficient of Y
A3 = Absolute coefficient

The final formula of active power losses as a function of transformation ratio and injected reactive power are introduced for each substation. Power losses due to transformation ratio and reactive power injected are given by the following expression:

$$Plosses = -0.0137*Qinj-0.7759*KT+30.3657$$

The optimum transformation ratio and optimum injected reactive power for maximum load operation is: KT = 0.330, Qinjected = 60 (Mvar).The minimum power losses due to optimum transformation ratio and optimum injected reactive power are: losses = 29.35 (MW) as shown in Table 3.

Table 3: Effect of tap changer and injected reactivepower on active power losses

Qinjected/KT	10 (Mvar)	20 (Mvar)	30 (Mvar)	40 (Mvar)	50 (Mvar)	60 (Mvar)
0.280	41.61	41.38	40.62	40.23	39.88	39.57
0.286	39.20	38.98	38.28	37.93	37.61	37.33
0.291	37.11	36.90	36.26	35.94	35.66	35.41
0.297	35.31	35.13	34.54	34.26	34.00	33.78
0.302	33.81	33.64	33.11	32.85	32.62	32.44
0.308	32.57	32.42	31.94	31.71	31.51	31.35
0.313	31.60	31.45	31.02	30.82	30.65	30.51
0.319	30.86	30.75	30.34	30.17	30.02	29.91
0.324	30.35	30.24	29.89	29.74	29.62	29.53
0.330	30.06	29.90	29.65	29.52	29.42	29.35
0.336	29.97	29.87	29.61	29.49	29.41	29.37
0.341	30.06	29.98	29.75	29.65	29.59	29.56
0.347	30.33	30.25	30.06	29.98	29.94	29.93
0.352	30.76	30.69	30.52	30.47	30.44	30.44
0.358	31.34	31.28	31.14	31.10	31.08	31.10
0.363	32.06	32.01	31.89	31.86	31.86	31.89
0.369	32.90	32.86	32.77	32.75	32.70	32.81
0.374	33.87	33.83	33.76	33.76	33.78	33.83
0.379	34.94	34.91	34.86	34.87	34.90	34.96

RESULTS AND DISCUSSION

Table 4 shows the results according to the calculations for power losses minimization in Jordanian electrical power system with automatic tap changing transformers (No. Interconnection System).

(At maximum loading): Table 5 shows the results according to the calculations for power losses minimization in a Jordanian electrical power system with reactive power injected (No Interconnection System).

Table 4: Results of calculations for power losses minimization in Jordanian electrical power system with automatic tap changing

Transformer (substation)	Normal position Transformation ratio		Optimal position Transformation ratio	Tap number	To optimize the performance of the electrical power system change tap from to
Amman South	0.330	0	0.341	2	0-2
Aqaba	0.324	-1	0.330	0	-1-0

Table 5: Results of calculations for power losses minimization in a jordanian electrical power system with reactive power injected

Transformer (substation)	Normal position transformation ratio	Optimal position transformation ratio	To optimize the performance of the electrical power system reactive power injected Mvar From	To
Amman South	2×40	2×45	2×40	2×45

CONCLUSION

The main findings of this study can be summarized as follows: optimizing operating modes of electrical power system can be made by controlling the transformation ratios and injected reactive power in main substations. Mathematical models are introduced to estimate the power losses using transformation ratios (and/or) injected reactive power using MATLAB program. And the optimal controlling variables for main substations are obtained. The proposed method also improves the voltage profile in the power system.

REFERENCES

Abdallah, J. and A.R. Al-Thaimer, 2003. Mathematical model of the load flow calculations using similarity relations. Intl. J. Appl. Math. Sofia Bulgaria, 14: 187-200.

Al-Thaimer, A.R., 2001. Simulating the effects of power transformers, tap changers on power losses. Proceedings of the International Middle Eastern Simulation Multiconference (MESM'01), September 3-5, 2001, Al-Ahliyya Amman University, Amman, Jordan, pp: 46-49.

Gonen, T., 1988. Modern Power System Analysis. John Wiley & Sons, New York, USA.,.

Liang, R.H., Y.K. Chen and Y.T. Chen, 2011. Volt-Var control in a distribution system by a fuzzy optimization approach. Intl. J. Electr. Power Energy Syst., 33: 278-287.

Liu, Y., P. Zhang and X. Qiu, 2002. Optimal volt-var control in distribution systems. Intl. J. Electr. Power Energy Syst., 24: 271-276.

Lukman, D. and T.R. Blackburn, 2003. Modified Algorithm of Load Flow Simulation For Losses Minimization in Power Systems. Institute of Electrical and Electronics Engineers, Sydney, New South Wales, Australia,.

NEPCO., 2015. Jordanian electrical power system parameters. National Electrical Power Company, Amman, Jordan.

Penny, J. and G. Lindfield, 1995. Numerical Methods using MATLAB. Ellis Horwood Ltd, Hertfordshire,.

Sarimuthu, C.R., V.K. Ramachandaramurthy, K.R. Agileswari and H. Mokhlis, 2016. A review on voltage control methods using on-load tap changer transformers for networks with renewable energy sources. Renewable Sustainable Energy Rev., 62: 1154-1161.

Weedy, B.M., 1979. Electric Power Systems. 3rd Edn., John Wiley & Sons, Hoboken, New Jersey, Pages: 538.