A Study of the Optimal Allocation of Shunt Capacitor Based on Modified Loss Sensitivity Algorithm

Warid Sayel Warid
Electrical Department
Technical Institute Shatra
Nasiriyah, Iraq
Email: sayelwarid@yahoo.com

Emad Allawi Mohsin
Electrical Department
Technical Institute Shatra
Nasiriyah, Iraq
Email: emad.almusawi@yahoo.com

Abstract—**Minimization of active power losses is one of the essential aims for any electric utility, due to its importance in improvement of system properties towards minimum production cost and to support increase load requirement. In this paper we have studied the possibility of reducing the value of real power losses for (IEEE-14- Bus bar) global system transmission lines by choosing the best location to install shunt capacitor depending on new algorithm for calculate the optimal allocation, which considering the value of real power losses derivative with injection reactive power as an indicator of the ability of reducing losses at load buses. The results show the validity of this method for application in electric power transmission lines.**

I. INTRODUCTION

Institutions of power generation aimed to raise operational efficiency to the possible extent by reducing the a mount of losses in real power transmitted a cross transmission lines, and also aims to maintain the quality of power supplied to users through voltage controlling within the permissible limits [1] ,therefore the need to use shunt capacitor as effective tool has been grown towards optimal control of reactive power. The first using of shunt capacitor began in 1914 for correct the value of power factor, and then be limited use for years to twenty-post, due to high value of the cost per kvar and the magnitude of the size and weight. Subsequently years witness tremendous progress in the design of the structure towards getting significantly reducing in size and weight of shunt capacitor [2]. In 1939 engineers can get significant decreasing in capacitor cost relative to its size, which leading to a strong entry into active service in power system, since that time the using of shunt capacitor increase steadily year after year [2].

Many researchers have been studied the optimal location for install shunt capacitor in electric power system. In [3] researchers suggested a method for choosing the optimal location for shunt capacitor allocation for 3-phase balanced and un balanced system towards reducing power losses and capacitor cost on one side and minimization distortion by harmonics on other side. A new technology for selective the optimal buses for shunt capacitor installing depending upon improvement in load bus voltages when using fixed quantity of reactive power within the allowed limits has been described in [4]. This technique has been applying on IEEE (30 -57) bus system. In [5] researchers developed three optimization algorithm and compare there result in order to obtain the best location and value of reactive power sources. This algorithm tested on (IEEE 14 bus system), also in [6] suggest method had been implemented for finding the optimal location for shunt capacitor using particle swarm optimization method and integrate with non linear interior point method. This technique had been applied on (New England 39 bus) test system. A new technique to install shunt capacitor at load buses introduced in [7] using a fuzzy technique to locate the best position for capacitor and using real coded genetic algorithm to determine its size. This technique had been tested on (15-34-69) test system.

II. REAL LOSSES FUNCTION

In this problem we need to find a function that represents the total real losses in transmission lines for any electrical power system. A non linear function based on the values and angles of network voltages as in : [8]

$$P_{Loss} = \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} \frac{G_{ij}}{2} [|V_i|^2 + |V_j|^2 - 2|V_i||V_j| Cos(\delta_i - \delta_j) \qquad (1)$$

P_{loss}: real power losses , i,j : bus number

III. THE MATHEMATICAL FORMULA

This formula using the sensitivity of real power losses with injection reactive power at load buses, as indicators of most and least effective locations in reducing the real losses, it was considered bus No. 1 as slack bus and follow with NL of load buses and NG of generation buses with voltage control (P.V), where N represent the total number of system buses as in

$$N = 1 + NL + NG \qquad (2)$$

For finding a solution using this method, we need to configure a vector containing the implicit derivatives of real losses with the voltage of load buses and voltage angles of all buses except slack bus. Since (1) based on the values and angles of system voltages. Therefore we can derive (1) to finding the element of the vector [D] as in

$$\frac{\partial P_{Loss}}{\partial \delta_i} = 2\sum_{\substack{j=1\\ j\neq i}}^{N} G_{ij}[|V_i||V_j|\,Sin(\delta_i - \delta_j)] \qquad (3)$$

$$\frac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{V_i}} = 2\sum_{\substack{\mathrm{j=1}\\ \mathrm{j\neq i}}}^{\mathrm{N}} \mathrm{G_{ij}}[|\mathrm{V_i}| - |\mathrm{V_j}|\mathrm{Cos}(\delta_\mathrm{i} - \delta_\mathrm{j})] \qquad (4)$$

$$[\mathrm{D}] = \begin{bmatrix} \dfrac{\partial \mathrm{P_{Loss}}}{\partial \delta_2} \\ \dfrac{\partial \mathrm{P_{Loss}}}{\partial \delta_3} \\ \vdots \\ \dfrac{\partial \mathrm{P_{Loss}}}{\partial \delta_\mathrm{N}} \\ \dfrac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{V_2}} \\ \dfrac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{V_3}} \\ \vdots \\ \dfrac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{V_{NL+1}}} \end{bmatrix} \qquad (5)$$

We also need to configure the Jacobin matrix resulting from the last iteration of load flow problem as in : [10]

$$[\mathrm{Jac}] = \begin{bmatrix} \dfrac{\partial P_2}{\partial \delta_2} & \cdots & \dfrac{\partial P_2}{\partial \delta_N} & \dfrac{\partial P_2}{\partial V_2} & \cdots & \dfrac{\partial P_2}{\partial V_{NL+1}} \\ \vdots & & \vdots & \vdots & & \vdots \\ \dfrac{\partial P_N}{\partial \delta_2} & \cdots & \dfrac{\partial P_N}{\partial \delta_N} & \dfrac{\partial P_N}{\partial V_2} & \cdots & \dfrac{\partial P_N}{\partial V_{NL+1}} \\ \dfrac{\partial Q_2}{\partial \delta_2} & \cdots & \dfrac{\partial Q_2}{\partial \delta_N} & \dfrac{\partial Q_2}{\partial V_2} & \cdots & \dfrac{\partial Q_2}{\partial V_{NL+1}} \\ \vdots & & \vdots & \vdots & & \vdots \\ \dfrac{\partial Q_{NL+1}}{\partial \delta_2} & \cdots & \dfrac{\partial Q_{NL+1}}{\partial \delta_N} & \dfrac{\partial Q_{NL+1}}{\partial V_2} & \cdots & \dfrac{\partial Q_{NL+1}}{\partial V_{NL+1}} \end{bmatrix} \qquad (6)$$

Using (5) and (6) we can obtain the following matrix equations

$$[\mathrm{Jac}]^\mathrm{T}\,[\mathrm{SEN}] = [\mathrm{D}] \qquad (7)$$

$$\therefore [\mathrm{SEN}] = [\mathrm{Jac}]^{\mathrm{T}^{-1}}\,[\mathrm{D}] \qquad (8)$$

$$\therefore \begin{bmatrix} \dfrac{\partial P_{Loss}}{\partial P_2} \\ \vdots \\ \dfrac{\partial P_{Loss}}{\partial P_N} \\ \dfrac{\partial P_{Loss}}{\partial Q_2} \\ \vdots \\ \dfrac{\partial P_{Loss}}{\partial Q_{NL+1}} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P_2}{\partial \delta_2} \cdots\cdots \dfrac{\partial P_N}{\partial \delta_2} & \dfrac{\partial Q_2}{\partial \delta_2} \cdots\cdots \dfrac{\partial Q_{NL+1}}{\partial \delta_2} \\ \vdots \qquad \vdots & \vdots \qquad \vdots \\ \dfrac{\partial P_2}{\partial \delta_N} \cdots\cdots \dfrac{\partial P_N}{\partial \delta_N} & \dfrac{\partial Q_2}{\partial \delta_N} \cdots\cdots \dfrac{\partial Q_{NL+1}}{\partial \delta_N} \\ \dfrac{\partial P_2}{\partial V_2} \cdots\cdots \dfrac{\partial P_N}{\partial V_2} & \dfrac{\partial Q_2}{\partial V_2} \cdots\cdots \dfrac{\partial Q_{NL+1}}{\partial V_2} \\ \vdots \qquad \vdots & \vdots \qquad \vdots \\ \dfrac{\partial P_2}{\partial V_{NL+1}} \cdots \dfrac{\partial P_N}{\partial V_{NL+1}} & \dfrac{\partial Q_2}{\partial V_{NL+1}} \cdots \dfrac{\partial Q_{NL+1}}{\partial V_{NL+1}} \end{bmatrix} \begin{bmatrix} \dfrac{\partial P_{Loss}}{\partial \delta_2} \\ \vdots \\ \dfrac{\partial P_{Loss}}{\partial \delta_2} \\ \dfrac{\partial P_{Loss}}{\partial V_2} \\ \vdots \\ \dfrac{\partial P_{Loss}}{\partial V_{NL+1}} \end{bmatrix} \qquad (8)$$

Where [SEN] is a sensitivity vector which represent the change in the a mount of real losses relative to injected real power at all buses except slack bus, and also gives the change in real losses relative to injected reactive power at load buses.

When neglecting the first (N-1) elements of sensitivity vector [SEN]. The resulting vector contain only the implicit derivative of real losses function relative to reactive power injected at load buses as in

$$[\mathrm{QSEN}] = \begin{bmatrix} \dfrac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{Q_2}} \\ \dfrac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{Q_3}} \\ \vdots \\ \dfrac{\partial \mathrm{P_{Loss}}}{\partial \mathrm{Q_{NL+1}}} \end{bmatrix} \qquad (9)$$

IV. RESULTS AND DISCUSSION

After finding all necessary derivative to complete the solution to the issue described above. The following step had been applied on the global system (IEEE 14 Bus-bar) for minimum and maximum load situations, where the power losses value was (13.39 Mw) at minimum load and (39.5 Mw) at maximum load, Table I. and Table II. represent the using method to indicate the location of shunt capacitor for the two cases. The tables contain a descending order for system buses upon the value of implicit derivative for real losses relative to injected reactive power which had been created for all buses from [QSEN] vector, we are assuming that the buses which have a high value of implicit derivative will be more efficient in reducing losses comparing with buses they have a small value of implicit derivative, and to prove the validity of this assumption we have used the following means:-

A. *Implicit derivative* $\frac{\partial P_{Loss}}{\partial Q_i}$

From Table I. for minimum load case we has select the bus No. 9 which have the highest value of implicit derivative (-0.01988) and select bus No. 7 which has a small value of the derivative (-0.0017) as sites for adding reactive power, also from Table II. for the maximum load case we have select bus No. 9 which has the highest value of implicit derivative (-0.02531) and bus No. 7 with small value (-0.0031) as sites for adding reactive power.

TABLE I. DESCENDING ORDER OF IMPLICIT DERIVATIVE FOR LOAD BUSES AT MINIMUM LOAD

No	Bus No.	$\frac{\partial P_{Loss}}{\partial Q_i}$
1	9	-0.01988
2	3	-0.01827
3	8	-0.01626
4	6	-0.01428
5	11	-0.01326
6	5	-0.01178
7	4	-0.01071
8	13	-0.0082
9	14	-0.00801
10	10	-0.0062
11	12	-0.0042
12	7	-0.0017

TABLE II. DESCENDING ORDER OF IMPLICIT DERIVATIVE FOR LOAD BUSES AT MAXIMUM LOAD

NO	Bus No	$\frac{\partial P_{Loss}}{\partial Q_i}$
1	9	-0.02531
2	3	-0.0241
3	6	-0.0221
4	8	-0.0217
5	11	-0.01827
6	5	-0.0162
7	4	-0.01437
8	13	-0.0127
9	14	-0.0118
10	12	-0.0098
11	10	-0.0072
12	7	-0.0031

After that we have recorded the value of the change in real losses with injected reactive power and sensitivity (implicit derivative) value for each of these load buses. From Fig. 1 and Fig. 3 we can see the decreasing of real power losses value gradually with increasing in the value of shunt capacitor at load buses (7,9) at minimum load situation until reach to the a point at which losses increase again. The best rate of loss minimization was (3.73%) for bus No. 9 and the worst rate was (0.50036%) for bus No.7 . From these results, we can conclude that the bus No. 9 has a great impact in reducing losses as compare with bus No. 7 and this supported previous assumption, Fig. 2 and Fig. 4 show the change of real power losses value with sensitivity of bus No. 9 and bus No. 7 at minimum load case. We can notice the decreasing of real power losses gradually against decreasing of sensitivity value until approaching to zero, where real losses value starting growing again. Therefore we can consider the value of sensitivity as an indicator of the point at which losses increasing and this point are the same for Fig. 1 and Fig. 3.

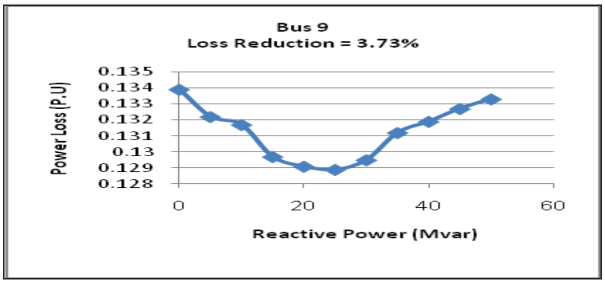

Fig. 1. Power loss versus reactive power at bus No. 9 for minimum load case

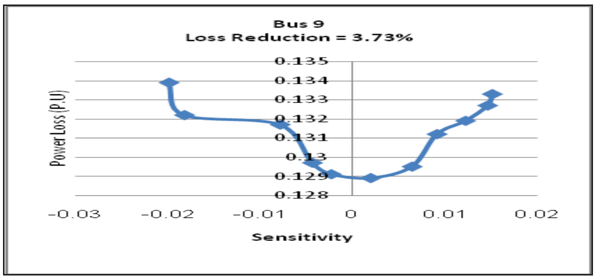

Fig. 2. Power loss versus sensitivity at bus No. 9 for minimum load case

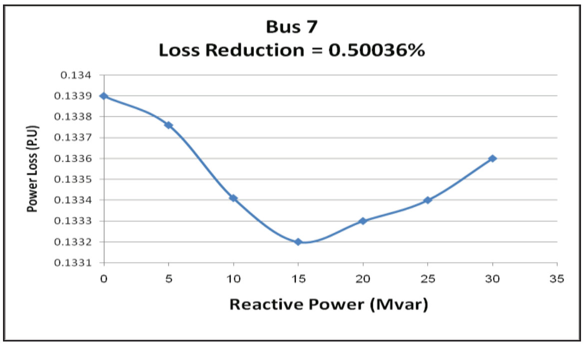

Fig. 3. Power loss versus reactive power at bus No. 7 for minimum load case

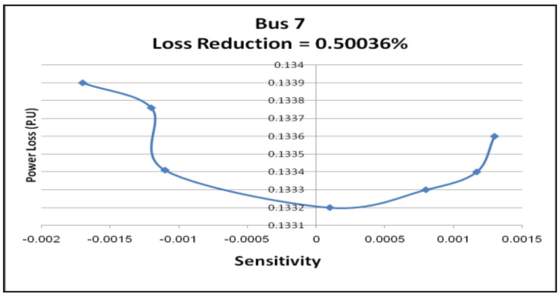

Fig. 4. Power loss versus sensitivity at bus No. 7 for minimum load case

From Fig. 5 and Fig. 7 we can notice a relation between real losses with injected reactive power at load buses No.7 and No. 9 at maximum load case. Where the value of losses minimization rate was (2.53%) for bus No. 9 and (0.759%) for bus No. 7, as can be for us to notice once again that both Fig. 6 and Fig. 8 illustrate the relationship between losses and the value of sensitivity and at same situation.

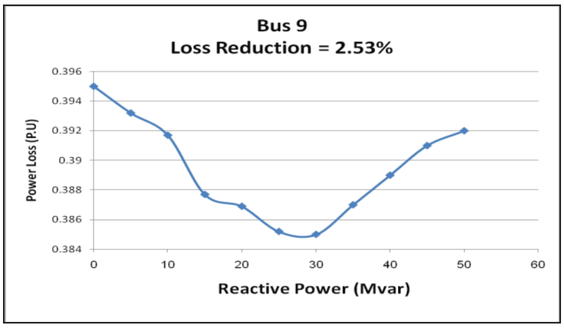

Fig. 5. Power loss versus reactive power at bus No. 9 for maximum load

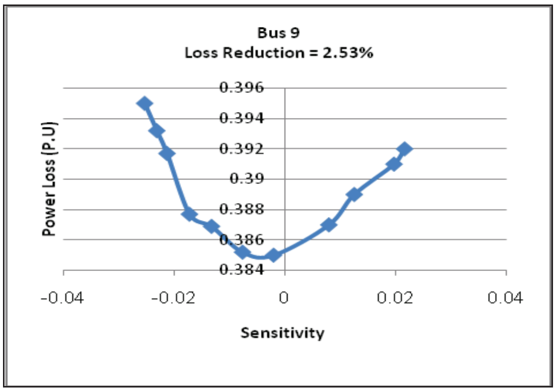

Fig. 6. Power loss versus sensitivity at bus No. 9 for maxmium load

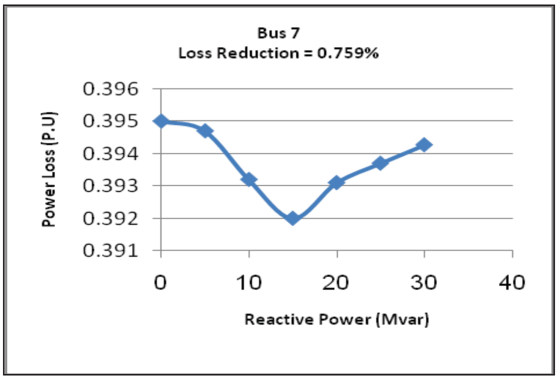

Fig. 7. Power loss versus reactive power at bus No. 7 for maximum load

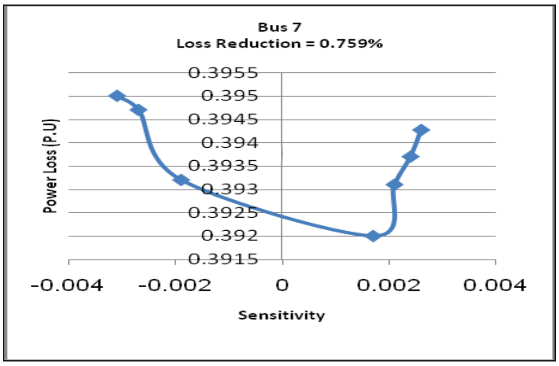

Fig. 8. Power loss versus sensitivity at bus No. 7 for maxmium load

After that and from Table I. for minimum load case we have select buses No . (9,3,8,6,11) which have a high value of implicit derivative as sites for adding reactive power (5Mvar) at the same time. Then we have run the load flow programm which result losses decrease to (11.84Mw) with excellent rate of losses minimization (11.57%), also from Table I. we have select buses No. (7,12,10,14,13) as sites for adding (5Mvar), losses decrease to (12.863Mw) with weak rate of losss minimization (3.93%).

From Table II. For maximum load case we have select buses No. (9,3,6,8,11) as sites for adding (5Mvar) at the same time. Losses decrease to (33.657Mw) with excellent rate of losses minimization (14.79%), also from Table II. we have select buses No. (7,10,12,14,13) as sites for adding (5Mvar) losses decrease to (37.8Mw) with weak rate of losses minimization (4.298%). The result have shown the success of suggested techniques in getting excellent rates of losses minimization when using a same value of reactive power for several load buses which have a high value of implicit derivative.

B. Constant value of reactive power

Adding shunt capacitor equivalent to (10Mvar) sequentially on each of load buses, Table III. and Table IV. contain a new descending order of load buses according to the value of losses minimization rate when adding (10Mvar) at all buses, and when compared it with the descending order in Table I. and Table II. which are based on the value of sensitivity. We find that the buses which locate at the top order and have a high value of sensitivity was the most viable to reduce a losses as shown in Table III. and Table IV. and this confirms the validity of the previous assumption. Therefore we can conclude that the change in the value of load does not lead to change in the order of buses which more efficient in reducing the losses.

TABLE III. DESCENDING ORDER OF LOSS MINIMIZATION RATE FOR LOAD BUSES AT MINIMUM LOAD

Bus No	Suggest Descending Order	Loss Minimization (%)
1	9	1.643
2	3	1.537
3	8	1.439
4	6	1.414
5	5	1.279
6	11	1.127
7	4	1.02
8	13	0.765
9	14	0.532
10	12	0.473
11	10	0.419
12	7	0.3659

TABLE IV. DESCENDING ORDER OF LOSS MINIMIZATION RATE FOR LOAD BUSES AT MAXIMUM LOAD

Bus No	Suggest Descending Order	Loss Minimization (%)
1	9	0.83544
2	3	0.8121
3	8	0.743
4	6	0.692
5	5	0.637
6	4	0.499
7	11	0.427
8	13	0.391
9	14	0.211
10	10	0.179
11	12	0.097
12	7	0.07595

Appendix I. Minimum Load Case

Bus No	Bus Type	Generation		Load	
		Active (MW)	Reactive (MVAR)	Active (Mw)	Reactive (MVAR)
1	Slack	232.39	-16.89	o	0
2	P.V	40	42.4	21.7	12.7
3	P.Q	0	23.39	94.2	19
4	P.Q	0	0	47.8	-3.9
5	P.Q	0	0	7.6	1.6
6	P.Q	0	12.24	11.2	7.5
7	P.Q	0	0	0	0
8	P.Q	0	17.36	0	0
9	P.Q	0	0	29.5	16.6
10	P.Q	0	0	9	5.8
11	P.Q	0	0	3.5	1.8
12	P.Q	0	0	6.1	1.6
13	P.Q	0	0	13.5	5.8
14	P.Q	0	0	14.9	5

Appendix II. Maximum Load Case

Bus No	Bus Type	Generation		Load	
		Active (MW)	Reactive (MVAR)	Active (MW)	Reactive (MVAR)
1	Slack	298.1	-22.81	0	0
2	P.V	40	38.1	24.2	13.8
3	P.Q	0	25.1	100.1	20.1
4	P.Q	0	0	48.1	-1.9
5	P.Q	0	0	10.2	1.8
6	P.Q	0	13.1	15.3	8.1
7	P.Q	0	0	0	0
8	P.Q	0	19.2	1	0
9	P.Q	0	0	35.1	17.1
10	P.Q	0	0	13.2	6.1
11	P.Q	0	0	4.8	2.2
12	P.Q	0	0	10.3	2.7
13	P.Q	0	0	17.2	6.2
14	P.Q	0	0	19.1	6.1

V. CONCLUSION

The results show the validity of considering the value of implicit derivative of real losses versus injected reactive power, as indicator of ability to reduce the losses at all selected load buses, as also noted a point at which losses increase again, as a result of continuous changing in the value of power transmitted between system lines depends on the values of network voltages and nature of problem constraints, also the result show stability of the order for efficient buses in reducing losses when the load change to another value, as shown in the selected two load situation.

The possibility of practical application of proposed formula by installing the shunt capacitor at selected load buses depending upon sensitivity value, and thus will be reduce the value of real losses significantly in the used system in addition to improvement voltage profile at load buses.

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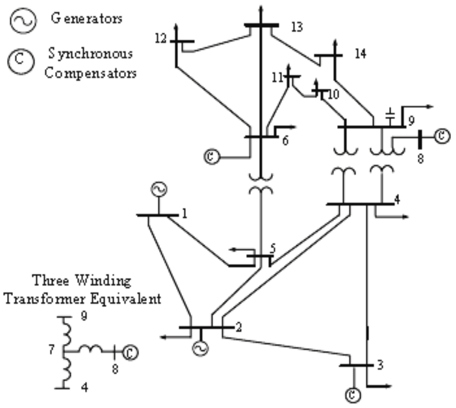

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