Shunt Capacitance for a Practical 110 kV System

A. H. Almasoud

EE Dept., Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia, P.O. Box 80204, Jeddah 21589
Email: amasoud@kau.edu.sa

Abstract: It is well known that shunt capacitance is both socially and economically beneficial to power system network. These devices reduce the apparent power (S) which is produced by generators allowing more customers to be served and increasing the income of electrical companies. Shunt compensation units have to be connected to carefully selected substations to result in a high degree of reactive power compensation. This can be done by several methods, such as the Genetic Algorithm (GA), Hybrid of GA or Trial and Error heuristic method. In this paper, we present a comparison of the three algorithms to determine the amount of savings that can be achieved by each algorithm. The system under investigation is a real 110 kV system, operating in the Western Region of Saudi Arabia, and the results reflect experimental data on this system.

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1.Introduction

The placement of a shunt capacitor within a power system network is not a trivial task. Several methods have been published to determine optimal shunt capacitor placement, such as the Trail and Error heuristic method, Artificial Neural Networks (ANN) method and Genetic Algorithm (GA) [1-17]. Because substations yield different reactive power savings, the proposed methods are useful in determining which substation would yield the greatest reactive power savings as a result of shunt capacitance placement.

In this paper, we present a comparison of the three algorithms to determine which algorithm would yield the greatest reactive power savings. The three methods were applied to a load flow computer program on a real power system network, containing several generators and 48 transmission lines (110kV). The 380 kV system compensation scientific paper was published [18].

2.110 kV System Topology

The system under investigation supplies a number of big cities in the Western region of Saudi Arabia as outlined in Fig. 1. The Western power system network can be represented in term of power production conditions, as shown in Table 1, by assuming that the cost of the production of each kWh is equivalent to $0.06 (6 cents). Three loading times were also considered i.e. peak, medium and light loading times. One hundred thirty seven substations (110/13.8 kV) supplying loads through the four major cities.

3.Shunt Capacitance Compensation

Capacitance units were placed on different substations (buses) in different main cities in the kingdom of Saudi Arabia, namely, Jeddah, Makkah, Madinah and Taif. Three algorithms (Trail and Error heuristic, Artificial Neural Networks (ANN) and Genetic Algorithm (GA)) are applied in order to find out the optimal places for shunt capacitance and then calculate the saving as a result. The calculations were carried out on three different loading times. That is to say when system loads are light, medium and peak. Saving have been found on three different times of loading throughout a year of consuming loads. The second major benefit of adding shunt capacitance is to reduce the distribution current throughout the power system network. This will reduce the power loss on transmission lines and cables. Thus more power can be transmitted via transmission lines and more customers can be absorbed as a result of adding shunt capacitances. Thirdly, shunt capacitances help stabilize buses voltages during heavy loaded system.

4.Four bus compensation in Jeddah city

In the first stage the computer program places a capacitor on one bus of the system and then find the bus that can give most reactive power compensation. In the second stage the computer program places two capacitors on two buses of the system and then find the two buses that can give most reactive power compensation provided that the bus No. that found from the first stage should be one of the two buses until finding the optimal two buses that can give most reactive power compensation. Similarly, for the third stage the computer program run to find the optimal three buses that give most reactive power compensation. In Jeddah city it is found that four bus compensation give the most reactive power compensation if they are connected simultaneously. The capacitance is then increased until the highest compensation of reactive power on those buses are achieved, provided that the generators are not converted to capacitive power generation. Table 2 shows that substations No. 150,140,190 and 220 yield the highest compensation during peak loading conditions which results in a 583.4 MVAR reduction of inductive production by the generators, corresponding to a 29.08% reduction in total generation (MVAR).

5.Triple bus compensation in Makkah city

In Makkah city it is found that the most reactive power compensation can be achieved if three buses were connected simultaneously. The capacitance is then increased until the highest compensation of reactive power on those buses are achieved, provided that the generators are not converted to capacitive power generation. Table 3 shows that substations No. 520,720 and 510 yield the highest compensation during peak loading conditions which results in a 420.7 MVAR reduction of inductive production by the generators, corresponding to a 20.97% reduction in total generation (MVAR).

6.Four bus compensation in Madinah city

In Madinah city it is found that the most reactive power compensation can be achieved if four buses were connected simultaneously. The capacitance is then increased until the highest compensation of reactive power on those buses are achieved, provided that the generators are not converted to capacitive power generation. Table 4 shows that substations No. 976,1090,1114 and 1040 yield the highest compensation during peak loading conditions which results in a 437.9 MVAR reduction of inductive production by the generators, corresponding to a 21.83 % reduction in total generation (MVAR).

7.Triple bus compensation in Taif city

In Taif city it is found that the most reactive power compensation can be achieved if three buses were connected simultaneously. The capacitance is then increased until the highest compensation of reactive power on those buses are achieved, provided that the generators are not converted to capacitive power generation. Table 5 shows that substations No. 580,640 and 550 yield the highest compensation during peak loading conditions which results in a 230.6 MVAR reduction of inductive production by the generators, corresponding to a 11.50 % reduction in total generation (MVAR).

7.Economic consideration

The three aforementioned methods, namely the Trial and Error heuristic method (proposed method), GA and GA + Hybrid, were applied to different buses of different city network to determine the greatest reduction of total MVAR generation during peak loading conditions. Using the results, the money savings for each method was calculated. Table 6 of Jeddah city shows that for a system with 7705 MVAR total generation, the proposed method yields saving equivalent to $1013440 per year. Table 7 of Makkah city shows that for the same system of generation, the GA, and GA+ Hybrid methods yield the same saving equivalent to $909765 per year. Table 8 of Madinah city shows that for the same system of generation the GA, and GA+ Hybrid methods yield the same saving equivalent to $489387 per year. Table 9 of Taif city shows for the same system of generation that the GA+ Hybrid method yields saving equivalent to $660560 per year. Moreover, the additional benefit for adding a shunt capacitor is that it allows the system to absorb more customers, thus increasing the total income of the electrical company and improving the capability of the system to withstand dip voltages.

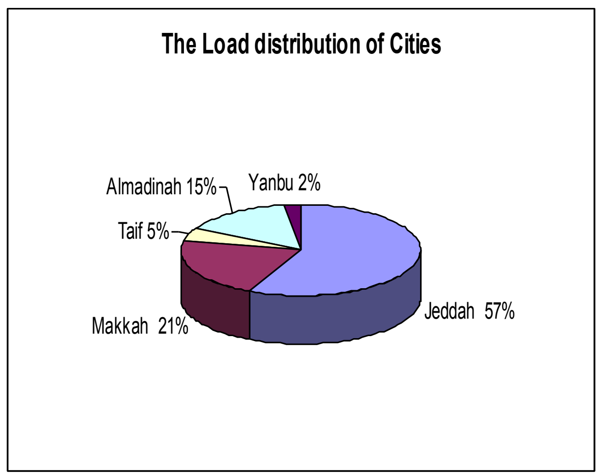

Figure 1 The percentage load distribution of cities at peak load

Table 1 System conditions prior to the capacitor placemen.

	Load Condition		
	Light	Medium	Peak
Total generated P (MW)	1,7543	4,150	7,440
Total generated Q (MVAR)	449	725.5	2,006
Total generated S (MVA)	1,811	4,213	7,705
Real power losses (kW)	6,200	24,900	71,400
Cost of Energy Losses ($)	814,680	6,543,720	9,381,960
Total Cost of Energy Losses ($/year)	16,740,360		

Table 2 Effect of four-shunt capacitor compensation on Jeddah network

System conditions prior to capacitor placement		Light Load	Medium Load	Peak Load
	Pg (pu)	1.7543	4.15	7.44
	Qg (pu)	0.449	0.7255	2.006
	Sg (pu)	1.811	4.213	7.705

BUS #				LOAD	Compensation Factor (%)				SIZE_ADDED (MVAR)				P gen. (PU)	Q gen. (PU)	S gen. (PU)	MVAR reduced	% red. in Qg	P-loss (PU)
150	140	190	220	Light	16	15	13	15	5	5	3	3	1.7543	0.4284	1.806	20.6	4.59	0.006
				Medium	15	25	37	33	5	7.5	7.5	7.5	4.1465	0.6941	4.204	31.4	4.33	0.022
				Peak	99	99	85	75	64	60	26	30	7.4373	1.4226	7.572	583.4	29.08	0.0678
150	140	210	220	Light	16	15	12	15	5	5	3	3	1.7543	0.4284	1.806	20.6	4.59	0.006
				Medium		25	24	33	5	7.5	7.5	7.5	4.1465	0.6941	4.204	31.4	4.33	0.022
				Peak	99	99	85	25	64	60	46	10	7.4372	1.4227	7.572	583.3	29.08	0.0678
150	140	60	200	Light	16	15	12	10	5	5	3	3	1.7543	0.4286	1.806	20.4	4.54	0.006
				Medium	16	15	31	27	5	5	7.5	7.5	4.1465	0.6973	4.204	28.2	3.89	0.022
				Peak	99	99	85	70	64	60	32	26	7.4373	1.4227	7.572	583.3	29.08	0.0678
150	140	210	450	Light	16	15	12	13	5	5	3	3	1.7543	0.4282	1.806	20.8	4.63	0.006
				Medium	20	15	24	30	5	5	7.5	7.5	4.1476	0.6975	4.206	28	3.86	0.023
				Peak	99	99	85	30	64	60	46	10	7.4373	1.4229	7.572	583.1	29.07	0.0678
150	140	182	190	Light	16	15	8	13	5	5	3	3	1.7543	0.4284	1.806	20.6	4.59	0.006
				Medium	16	25	12	37	5	7.5	7.5	7.5	4.1465	0.6941	4.204	31.4	4.33	0.022
				Peak	99	99	85	80	64	60	31	25	7.4373	1.4229	7.572	583.1	29.07	0.0678

Table 3 Effect of triple-shunt capacitor compensation on Makkah network

System conditions prior to capacitor placement		Light Load	Medium Load	Peak Load
	Pg (pu)	1.7543	4.15	7.44
	Qg (pu)	0.449	0.7255	2.006
	Sg (pu)	1.811	4.213	7.705

BUS #			LOAD	Compensation Factor (%)			SIZE-ADDED (MVAR)			P gen. (PU)	Q gen. (PU)	S gen. (PU)	MVAR reduced	% red. in Qg	P-loss (PU)
520	720	510	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	31	23	29	10	10	10	4.1475	0.6864	4.204	39.1	5.39	0.023
			Peak	55	55	96	24	26.5	42.5	7.4373	1.5853	7.6044	420.7	20.97	0.0678
840	720	510	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	25	23	29	10	10	10	4.1475	0.6874	4.204	38.1	5.25	0.023
			Peak	55	55	96	31	26.5	42.5	7.4373	1.5867	7.6047	419.3	20.90	0.0678
520	840	510	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	31	25	29	10	10	10	4.1475	0.6867	4.204	38.8	5.35	0.023
			Peak	55	55	96	24	31	42.5	7.4373	1.5876	7.6048	418.4	20.86	0.0678
720	780	510	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	23	26	29	10	10	10	4.1475	0.6879	4.204	37.6	5.18	0.023
			Peak	55	55	96	27	24.5	42.5	7.4376	1.6027	7.6083	403.3	20.10	0.0681
520	780	510	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	31	26	29	10	10	10	4.1475	0.687	4.204	38.5	5.31	0.023
			Peak	55	55	96	24	24.5	42.5	7.4376	1.6036	7.6085	402.4	20.06	0.0681

Table 4 Effect of four-shunt capacitor compensation on Madinah network

System conditions prior to capacitor placement		Light Load	Medium Load	Peak Load
	Pg (pu)	1.7543	4.15	7.44
	Qg (pu)	0.449	0.7255	2.006
	Sg (pu)	1.811	4.213	7.705

BUS #				LOAD	Compensation Factor (%)				SIZE_ADDED (MVAR)				P gen. (PU)	Q gen. (PU)	S gen. (PU)	MVAR reduced	% red. in Qg
976	1090	1114	1040	Light	50	99	99	99	25	20	20	20	1.7543	0.3763	1.7942	72.7	16.19
				Medium	88	87	99	99	30	20	20	20	4.1465	0.684	4.2025	41.5	5.72
				Peak	99	99	99	99	35.5	48.5	63	53	7.4396	1.5681	7.603	437.9	21.83
990	1090	1114	1040	Light	99	99	99	99	10	20	20	20	1.7543	0.3791	1.7948	69.9	15.57
				Medium	77	87	99	99	10	20	20	20	4.1465	0.6941	4.204	31.4	4.33
				Peak	99	99	99	99	28.5	48.5	63	53	7.4398	1.5781	7.6054	427.9	21.33

976	1060	1114	1040	Light	50	99	99	99	25	20	20	20	1.7543	0.3777	1.7945	71.3	15.88
				Medium	88	87	99	99	30	20	20	20	4.1465	0.69	4.2035	35.5	4.89
				Peak	99	99	99	99	35.5	39.5	63	53	7.4395	1.5805	7.6056	425.5	21.21
976	1050	1114	1040	Light	50	99	99	99	25	20	20	20	1.7543	0.3802	1.7950	68.8	15.32
				Medium	88	99	99	99	30	20	20	20	4.1465	0.694	4.204	31.5	4.34
				Peak	99	99	99	99	35.5	39.5	63	53	7.4396	1.5808	7.6056	425.2	21.20
976	1035	1114	1040	Light	50	99	99	99	25	15	20	20	1.7543	0.3864	1.7964	62.6	13.94
				Medium	88	80	99	99	30	20	20	20	4.1465	0.696	4.2045	29.5	4.07
				Peak	99	99	99	99	35.5	38.5	63	53	7.4395	1.5817	7.6058	424.3	21.15

Table 5 Effect of triple-shunt capacitor compensation on Taif network.

		Light Load	Medium Load	Peak Load
System conditions prior to capacitor placement	Pg (pu)	1.7543	4.15	7.44
	Qg (pu)	0.449	0.7255	2.006
	Sg (pu)	1.811	4.213	7.705

BUS #			LOAD	Compensation Factor (%)			SIZE-ADDED (MVAR)			P gen. (PU)	Q gen. (PU)	S gen. (PU)	MVAR reduced	% red. in Qg	P-loss (PU)
580	640	550	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	99	99	83	10	20	15	4.1475	0.664	4.200	61.5	8.48	0.023
			Peak	99	94	99	12	21.5	22	7.4397	1.7754	7.6486	230.6	11.50	0.0699
580	620	550	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	99	88	83	10	15	15	4.1475	0.669	4.201	56.5	7.79	0.023
			Peak	99	99	99	12	21	22	7.4397	1.7758	7.6487	230.2	11.48	0.07021
580	610	550	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	99	96	83	10	15	15	4.1475	0.669	4.201	56.5	7.79	0.023
			Peak	99	99	99	12	21	22	7.4397	1.7761	7.6488	229.9	11.46	0.07021
580	630	550	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	99	96	83	10	30	15	4.1475	0.654	4.199	71.5	9.86	0.023
			Peak	99	69	99	12	21	22	7.4397	1.7762	7.6488	229.8	11.46	0.07022
630	660	550	Light	0	0	0	0	0	0	1.7543	0.449	1.811	0	0	0.0062
			Medium	96	99	83	30	5	15	4.1475	0.659	4.199	66.5	9.17	0.023
			Peak	99	64	99	30	3.5	22	7.4397	1.7762	7.6488	229.8	11.46	0.07024

Table 6 Optimum solution of shunt capacitor compensation on Jeddah network.

		Light Load	Medium Load	Peak Load
System values prior to capacitor placement	Pg (pu)	1.7543	4.15	7.44
	Qg (pu)	0.449	0.7255	2.006
	Sg (pu)	1.811	4.213	7.705

	Proposed Method			GA Method			(GA+Hyb) Method		
Shunt Compensated Bus No's.	140, 150, 190, 220			140, 150, 190, 220, 270, 310			140, 150, 190, 220, 270, 310		
Load Case	Light	Medium	Peak	Light	Medium	Peak	Light	Medium	Peak
Shunt Added Mvar	5, 5, 3, 3,	7, 5, 7, 7,	60, 64, 26, 30,	7, 8, 10 0, 0, 0	13,10,10 7, 0, 0	57,47,30 14,10,9	8, 9, 5 0, 0, 0	12,10,5 5, 0, 0	48,55,28 37, 4, 5
Generated P (PU)	1.7541	4.1465	7.4374	1.7543	4.1465	7.4374	1.7543	4.1465	7.4373
Generated Q (PU)	0.4284	0.6941	1.4226	0.449	0.6941	1.4478	0.449	0.6941	1.431
Generated S (PU)	1.8057	4.2042	7.5722	1.8108	4.2042	7.5770	1.8108	4.2042	7.5737
Reduced MVAR	20.60	31.40	583.40	0.00	31.40	558.20	0.00	31.40	575.00
% Reduction in Qg	4.59	4.33	29.08	0.00	4.33	27.83	0.00	4.33	28.66
Power Losses (PU)	0.006	0.022	0.0678	0.006	0.022	0.06793	0.006	0.022	0.067803
Capacitors Cost ($/year)	16,000	52,000	180,000	25,000	80,000	167,000	22,000	64,000	176,000
Power Loss Cost ($/year)	788,400	5,781,600	8,908,920	788,400	5,781,600	8,925,989	788,400	5,781,600	8,909,314
Total System Cost ($/year)	804,400	5,833,600	9,088,920	813,400	5,861,600	9,092,989	810,400	5,845,600	9,085,314
Savings ($/year)	10,280	710,120	293,040	1,280	682,120	288,971	4,280	698,120	296,646
TOTAL SYSTEM SAVINGS ($/year)	1,013,440			972,371			999,046		

Table 7 Optimum solution of shunt capacitor compensation on Makkah network.

System values prior to capacitor placement		Light Load	Medium Load	Peak Load
	Pg (pu)	1.7543	4.15	7.44
	Qg (pu)	0.449	0.7255	2.006
	Sg (pu)	1.811	4.213	7.705

	Proposed Method			GA Method			(GA+Hyb) Method		
Shunt Compensated Bus No's.	510, 520, 720			510, 520, 720			510, 520, 720		
Load Case	Light	Medium	Peak	Light	Medium	Peak	Light	Medium	Peak
Shunt Added Mvar	0, 0, 0	10, 10, 10	43, 24, 27	0, 0, 0	7, 7, 7	42, 41, 46	0, 0, 0	7, 7, 7	42, 41, 46
Generated P (PU)	1.7543	4.1475	7.4373	1.7543	4.1475	7.4365	1.7543	4.1475	7.4365
Generated Q (PU)	0.4490	0.6860	1.5853	0.4490	0.6900	1.4832	0.4490	0.6900	1.4832
Generated S (PU)	1.8108	4.2038	7.6044	1.8108	4.2045	7.5830	1.8108	4.2045	7.5830
Reduced MVAR	0.00	39.50	420.70	0.00	35.50	522.80	0.00	35.50	522.80
% Reduction in Qg	0.00	5.44	20.97	0.00	4.89	26.06	0.00	4.89	26.06
Power Losses (PU)	0.0062	0.0228	0.0678	0.0062	0.0230	0.0670	0.0062	0.0230	0.0670
Capacitors Cost ($/year)	0	60,000	94,000	0	42,000	129,000	0	42,000	129,000
Power Loss Cost ($/year)	814,680	5,978,700	8,908,920	814,680	6,044,400	8,800,515	814,680	6,044,400	8,800,515
Total System Cost ($/year)	814,680	6,038,700	9,002,920	814,680	6,086,400	8,929,515	814,680	6,086,400	8,929,515
Savings ($/year)	0	505,020	379,040	0	457,320	452,445	0	457,320	452,445
TOTAL SYSTEM SAVINGS ($/year)	884,060			909,765			909,765		

Table 8 Optimum solution of shunt capacitor compensation of Madinah network.

System values prior to capacitor placement		Light Load	Medium Load	Peak Load
	Pg (pu)	1.7543	4.15	7.44
	Qg (pu)	0.449	0.7255	2.006
	Sg (pu)	1.811	4.213	7.705

	Proposed Method			GA Method			(GA+Hyb) Method		
Shunt Compensated Bus No's.	1040, 1060, 1090, 1114			1040, 1060, 1090, 1114			1040, 1060, 1090, 1114		
Load Case	Light	Medium	Peak	Light	Medium	Peak	Light	Medium	Peak
Shunt Added Mvar	0, 0, 0, 0	20, 20, 10, 20	30, 20, 10, 40	0, 0, 0, 0	0, 15, 6, 9	1, 20, 6, 9	0, 0, 0, 0	0, 15, 6, 9	1, 20, 6, 9
Generated P (PU)	1.7543	4.1465	7.4395	1.7543	4.1475	7.4403	1.7543	4.1475	7.4403
Generated Q (PU)	0.4490	0.696	1.5817	0.4490	0.666	1.8202	0.4490	0.666	1.8202
Generated S (PU)	1.8108	4.2045	7.6058	1.8108	4.2006	7.6597	1.8108	4.2006	7.6597
Reduced MVAR	0.00	29.50	424.30	0.00	59.50	185.80	0.00	59.50	185.80
% Reduction in Qg	0.00	4.07	21.15	0.00	8.20	9.26	0.00	8.20	9.26
Power Losses (PU)	0.0062	0.0228	0.0701	0.0062	0.023	0.070745	0.0062	0.023	0.070745
Capacitors Cost ($/year)	0	140,000	100,000	0	60,000	36,000	0	60,000	36,000
Power Loss Cost ($/year)	814,680	5,991,840	9,211,140	814,680	6,044,400	9,295,893	814,680	6,044,400	9,295,893
Total System Cost ($/year)	814,680	6,131,840	9,311,140	814,680	6,104,400	9,331,893	814,680	6,104,400	9,331,893
Savings ($/year)	0	411,880	70,820	0	439,320	50,067	0	439,320	50,067
TOTAL SYSTEM SAVINGS ($/year)	482,700			489,387			489,387		

Table 9 Optimum solution of shunt capacitor compensation of Taif network.

System values prior to capacitor placement		Light Load	Medium Load	Peak Load
	Pg (pu)	1.7543	4.15	7.44
	Qg (pu)	0.449	0.7255	2.006
	Sg (pu)	1.811	4.213	7.705

	Proposed Method			GA Method			(GA+Hyb) Method		
Shunt Compensated Bus No's.	550, 580,620			550, 580, 620			550, 580, 620		
Load Case	Light	Medium	Peak	Light	Medium	Peak	Light	Medium	Peak
Shunt Added Mvar	0, 0, 0	0, 9,0	16, 10, 4	0, 0,0	5, 9,0	9, 9,0	0, 0, 0	5, 10, 0	7, 10, 2
Generated P (PU)	1.7543	4.1475	7.4397	1.7543	4.1475	7.4393	1.7543	4.1475	7.4393
Generated Q (PU)	0.4490	0.669	1.7754	0.4490	0.664	1.785	0.4490	0.66	1.7854
Generated S (PU)	1.8108	4.2011	7.6486	1.8108	4.2003	7.6505	1.8108	4.1997	7.6505
Reduced MVAR	0.00	56.50	230.60	0.00	61.50	221.00	0.00	65.50	220.60
% Reduction in Qg	0.00	7.79	11.50	0.00	8.48	11.02	0.00	9.03	11.00
Power Losses (PU)	0.0062	0.023	0.0699	0.0062	0.02305	0.069808	0.0062	0.023	0.0698
Capacitors Cost ($/year)	0	18,000	30,000	0	28,000	18,000	0	30,000	19,000
Power Loss Cost ($/year)	814,680	6,044,400	9,184,860	814,680	6,057,540	9,172,771	814,680	6,044,400	9,171,720
Total System Cost ($/year)	814,680	6,062,400	9,214,860	814,680	6,085,540	9,190,771	814,680	6,074,400	9,190,720
Savings ($/year)	0	481,320	167,100	0	458,180	191,189	0	469,320	191,240
TOTAL SYSTEM SAVINGS ($/year)	648,420			649,369			660,560		

Conclusions

It is well known that shunt capacitances added value to power system networks. The 110 kV system under investigation represents a real system, operating in the Western region of the Kingdom of Saudi Arabia, with the capacity of 7705MVA in 2003. The three methods investigated showed saving ranging according to the results shown in Tables 6-9. Based on study, it is recommended that the electrical companies have to consider applying shunt capacitors to their electrical substations. It is recommended that the shunt capacitances should be of automatic variable values in order to suit different time of loading and to keep the generating system to be reactive power production and not capacitive power production. This study indicates that if the data of the system are for this year, the compensation will be bigger than the calculated one and the savings as well. The study was not an easy task since the collecting data took time and the programming also took some time and the program testing took another extra time in order to check the results come out of the load flow computer program to be matched with the results of the load flow of the Saudi electrical company. This check is important and it is the first step to start to use the developed computer program in applying shunt compensation and finding the optimal buses that can be used for compensation and trusting the results.

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