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Original Article

Optimal Capacitor Placement Using Tabu Search Algorithm to Improve the Operational Efficiency in GEPCO Network

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***Abstract* — *Capacitor banks provide local to the system and are utilized for improvement of operational parameters in distribution network from last few decades. Optimal capacitor placement has a number of advantages, such as improvement in voltage profile, reduction in technical losses, and increasing the availability of additional MVA capacities of power system equipment. A case study is presented here in which two express networks of GEPCO (SCARP 1 & 2) are analyzed, and capacitor bank sizing and locations are optimized using the Tabu search algorithm. DIgSILENT power factory software is used to model the network with real-time data, and the results obtained are compared with actual locations. These results show that the algorithm is robust enough to apply for optimization purposes in larger networks.*

Keywords — *Tabu search algorithm, optimization, DIgSILENT, capacitor bank, technical losses, sub-transmission system.*

I. INTRODUCTION

Any energy saving by improving efficiency can be regarded as a valuable asset for an energy starving country. Like other developing countries, Pakistan faces a demand-supply gap in major energy sectors from mild to acute levels. This gap may be considered an indicator of the rapid growth of a country compared to its infrastructure development. The overwhelming usage of electrical energy demands infrastructure and is therefore increasing network complexities by many folds. Exponential growth in the usage of electronic devices and ingress of distributed generation sources (DGS) in distribution companies (DISCOs) networks has created serious power quality issues. Transmission company (NTDCL) in Pakistan is responsible for 660 kV DC, 500 & 220 kV AC OHTL of medium and long lengths, whereas DISCOs are responsible for short length sub-transmission network of 132 kV.

The ever-increasing electrical energy demand at an exponential rate has caused depletion of the generation sources and supply infrastructure. This over-expanding supply network has caused excessive length and loading, resulting in large voltage drops, poor voltage regulations, and increased losses. Since operational parameters are monitored by an independent watchdog, NEPRA and penalize the DISCOs for violations. Hence it becomes of immense importance for the DISCOs to maintain the system parameters within permissible limits.

The application of fixed and switched capacitors on the distribution system to support voltage profile and power factor is globally popular. However, proper sizing and finding the feasible location of the capacitor bank are of extreme importance. The efficacy of capacitor banks is greatly reduced if not correctly sized and located. Hence the optimization techniques become essential for these real-world issues. Most of the blackouts in the world, particularly in Pakistan, are caused by voltage instabilities and human errors. There are various optimization techniques for capacitor bank sizing and finding appropriate locations in the radial network, such as ant colony search algorithm [1], particle swarm optimization [2], Monte Carlo algorithm [3], plant growth optimization [4], shark smell optimization [5], firefly optimization [6], flower pollination optimization [7], dynamic programming optimization and genetic algorithm (GA) [8] got remarkable improvement in operational parameters of the system under consideration. Some recently proposed an improved method using GA and applied it successfully to switched capacitors [9],[10].

In this paper, a very simple, easy to implement, and the practical algorithm is applied for optimal capacitor placement (OCP) in SCARP 1 & 2 express networks. This algorithm can handle the capacitor bank sizing, location, financial analysis, and finding the optimal switching timings to keep the system parameters within permissible limits. Switching time varies with location, season, and consumer type connected to the network. This method finds an optimal solution by using standard capacitor sizes, actual cost, and load profile of the network with ease. DIgSILENT power factor (DPF), one of the leading electrical network simulation software, is utilized for system modeling and OCP solution. The results are compared with the on-site data of GEPCO.

II. GEPCO & PROBLEM FORMULATION

GEPCO is one of the ten DISCOs unbundled from the power wing of WAPDA. Its jurisdiction is densely populated six districts of Punjab province, as shown in Fig. 1. It is a hub of small and medium level industry, agricultural dominated areas, commercial centers, and electrical energy to domestic consumers. Peak demand for May 2020 was about 3000 MW and decreased to about 1000 MW in winter Season.

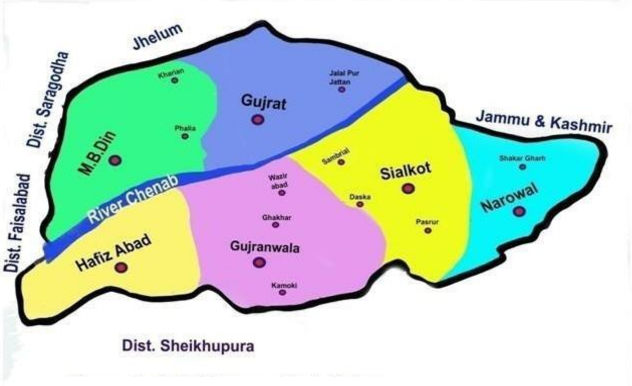


Fig. 1 GEPCO area of jurisdiction

Management is striving hard to reduce losses by employing every possible means. Like any other world-class company, GEPCO is trying to provide reliable, stable, and good quality electrical energies to end-users and cope with ever-growing demand with minimal technical losses. SCARP 1 & 2, two express networks of 132 kV, originating from Mangla hydal power plant, provide electrical energy to GEPCO and a part of FESCO territory, as shown in Fig. 2. These are radial and yet have no DGS connections. The length of GEPCO territory is about 200 Km for each of these feeders and therefore always facing poor power quality issues, which becomes even worse in the summer season.

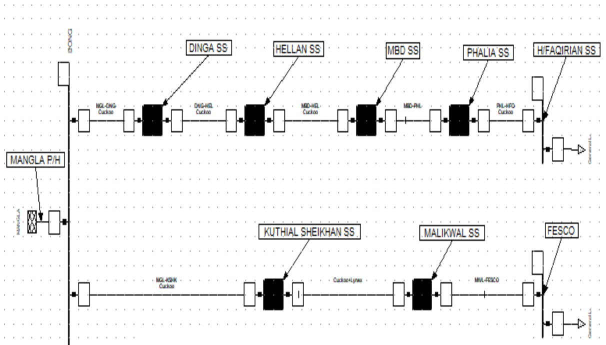


Fig. 2 SCARP 1 & 2 networks

Network data, voltage profile, losses, and peak loading conditions for May 2020 are given in Table 1 and Table 2. As per measured data, the voltage profile of the whole system was below threshold limits of ±10% and needed some corrective actions. The area supplied by this network is mostly rural, has lengthy feeders, and comprises non-industrial consumers.

During the study following assumption has been made:

- Loading data of May 2020 is used.
- 40A & 120A current flows from FESCO network from F-1 & F-2 respectively.
- Fixed capacitors are considered for the optimization process as per the previous practice of DISCO.
- Due to consideration of a single load state, the switching time of the capacitor bank is not part of optimization.
- 48 MVAR capacitor bank is already installed at the MBD bus bar, whereas 24 MVAR at Kuthiyala Sheikhan.

A. Problem Formulation

This work aims to find the optimum locations and sizes of fixed type shunt capacitor banks to keep the voltage of bus bars, power factor, and losses of the system within permissible limits. Like any other engineering task, financial analysis will also be carried out to check the benefit to cost ratio of the final findings. The OCP algorithm minimizes the total annual cost given by equation (1) while keeping an eye on constraint factors of acceptable voltages and installation, operation, and maintenance costs.

Table 1. Operational Parameters of the network before OCP

Sr. NO	**Bus Name**	**V [kV]**	**P [MW]**	**Q [MVAR]**	**I [A]**	**θ [-deg]**
1	Dinga	113.2	20.3	9.8	115	12.89
2	Hillan	110.1	27.2	9.8	159	16.43
3	MBD	106.2	34.8	13.2	210	21.7
4	Phalia	103.9	22.9	16.9	141	22.81
5	K-Sheikhan	115,9	38.7	11.1	214	12.71
6	Malikwal	113.7	16.7	7.0	92	14.77

Table 2. Line parameters & associated voltage drop before OCP

Sr. No.	**From (Bus Bar)**	**To (Bus Bar)**	**Conductor Type (ACSR)**	**Length (km)**	**Loading (%)**	**Voltage drop (kV)**
1	Bong	Dinga	Cuckoo	72	80.4	18.82
2	Dinga	Hellan	Cuckoo	20	65.8	3.11
3	Hellan	M.B.Din	Cuckoo	20	74.2	3.86
4	M.B.Din	Phalia	Cuckoo + Lynex	16+24=40	39.6	2.28
5	Phalia	H/Faqiryan (FESCO)	Cuckoo	46.23	6.6	1.03
6	Bong	K-Sheikhan	Cuckoo	110	50.2	16.07
7	K-Sheikhan	Malikwal	Cuckoo + Rail	3.25+23.06 = 26.31	26.9	2.20

Where

- C_{Loss} is the total loss caused by I^2R in all the elements of the network.
- C_{CAP} is the capacitor bank's annual cost, including investment, insurance, and maintenance up to 'm' number of capacitors.
- $C_{V\text{-}Violations}$ is the fictitious cost used to penalize when bus voltage varies out of permissible limits of ±10%.

III. DPF & OPTIMIZATION ALGORITHM

DPF is used for OCP purposes on the network under consideration. It is the most economical solution, has extensive data handling and flexible modeling capabilities. DPF is a handy tool with a rich suit of built-in equipment libraries and unlimited opportunities in optimization based on scripting functionalities. OCP algorithm determines the optimal location, sizes, and switching time (optional) in a radial distribution network. It evaluates the annual overall capacitor installation charges against the economic benefits due to reduction of losses while keeping the voltage profile of the network within permissible limits. DPF can conduct loss sensitivity analysis for the radial feeder to locate the candidate busses for the OCP that complies with all the constraints.

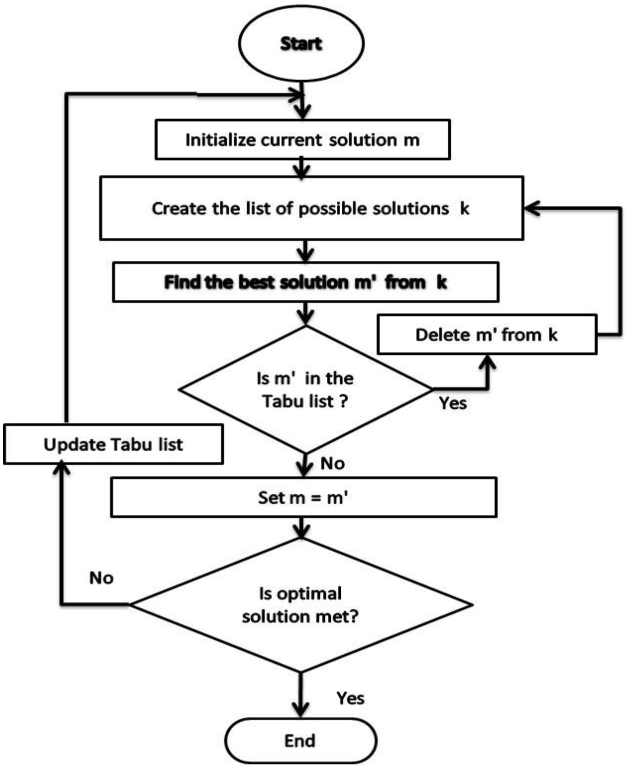


Fig. 3 Tabu search algorithm flow chart

A. Tabu Search Algorithm

Tabu search algorithm (TSA) is a meta-heuristic search method that guides search procedures to explore outside the local optimum using tabu's short-term memory list. It is based upon a hill-climbing algorithm and, due to the tabu list, will avoid already visited nodes for a short time to reach out to the global best solution. It applies to both continuous and discrete natured optimization problems and is so applied here for OCP purposes. The flow chart of TSA is shown in Fig. 3. Some of the key benefits of TSA are given below:

- Each step of this algorithm evaluates the solution and ensures effective computing with each iteration.
- Keeping the record of each visited node and its associated solution enables this to reach the global optimum solution.
- The search is diversified, and it ensures that less-visited regions of search space are also considered.

IV. LOCATING CANDIDATE BUSSES

DPF carries out loss sensitivity analysis (LSA) to identify the suitable locations for OCP in feeders, one by one at each node. In our case, two feeders from the Bong bus bar are defined for LSA and the OCP in the DPF environment, as shown in Fig. 2. It predicts the buses where capacitor placement will result in considerable loss reduction. In LSA, available capacitors in a user-definable library and combinations are installed at all network busses (HV & LV). Capacitors are selected in an ascending capacity order, and the peak reactive power load determines the final size.

At the final stage of LSA, the annual system cost is evaluated for all combinations on entire network busses, and the best busses are selected for TSA initial search space as a candidate. This helps in the reduction of search space for TSA and processing time to reach the optimal solution. Feeder-1 (F-1) includes 132 kV busses, i.e., Dinga, Hillan, MBD, Phalia, and Head Faqiriyan, whereas feeder-2 (F-2) contains Kuthiyala Sheikhan, Malikwal, and FESCO bus bars. The summary of both feeders before the start of LSA is checked and is given in Table 2, whereas the annual system cost of both feeders is given in Table 3.

Table 3. Feeder voltage and losses before OCP

Sr. No	Feeder	Losses (MW)	Min. Voltage (p.u)
1	F-1	9.603	0.78
2	F-2	3.999	0.843

Table 4. LSA annual cost result for feeders 1 & 2 (ascending order)

Sr. No	Feeder	Candidate Bus [132 kV]	Cost (PKR)
1	F-1	Hillan	33,39,807.12
2		Dinga	33,73,090.12
3		MBD	34,45,129.14
4		Phalia	34,40,265.34
5		Head Faqiriyan	34,88,154.68
6	F-2	Kuthiyala Sheikhan	36,17,065.30
7		Malikwal	36,20,234.24
8		FESCO	36,56,322.64

LSA arranges the candidate busses in descending order of cost reduction, excluding the capacitor cost, and during the TSA optimization process, it helps reduce time in finding the optimal solution.

V. OCP ALGORITHM EVALUATION

OCP algorithm evaluated all three cost affecting factors mentioned in equation (1) & after that

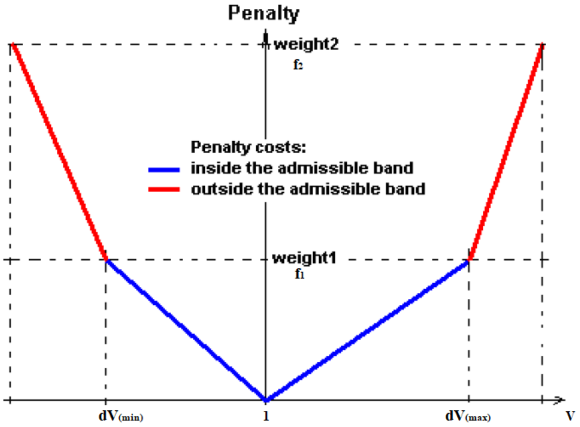


Fig. 4 Fictitious cost assigned by voltage range violations

The final decision is made. $C_{(Loss)}$ and $C_{(CAP)}$ are calculated in the standard way given in eq-(1) above for every iteration during LSA by connecting the largest available capacitor(s), whereas $C_{(V\text{-}violation)}$ is calculated in a different way. It is a fictitious kind of cost that helps OCP algorithm to keep the voltage of all the feeder nodes within permissible limits (In Pakistan, 132±10% kV and 400/230 ±5% V). The algorithm evaluates two types of voltage violation cost factors given by equation (2).

$$C_{(V\text{-}violation)} = C_1 + C_2 \qquad (2)$$

Where

$C_1 = f_1 \, . \, \Delta V$
$C_2 = f_2 . \, (\Delta V - \Delta V_{max/min}) + C_1$

C_1 is the cost involved when voltage is in permissible range with f_1 as the weighted penalty factor during this situation, whereas C_2 is the cost involved when voltage violations are outside ±10% band of rated voltage. Fig. 4 illustrates the concept of voltage violation cost [11].

VI. RESULTS FOR SCARP 1 & 2 NETWORK

OCP study finds the feasible size and location for installing new capacitor banks to keep the operational parameters of the network within permissible limits. Installation of 36 MVAR at 132 kV bus bar of Hillan substation in F-1 and an additional 24 MVAR at Kuthiyala Sheikhan bus bar of F-2 will bring the whole network in a better position even if not in an ideal one. It improves the operating voltage and brings it in permissible range, reduces feeder losses drastically, and spare MVA capacity of power system equipment for the future. This OCP practice will also save the cost of system expansion as extra MVA capacity will be available in transmission lines, power transformers, and cables. Table-5 shows the operational parameters, and Table-6 contains a feeder summary after OCP.

Table 5. Operational parameters of network after OCP

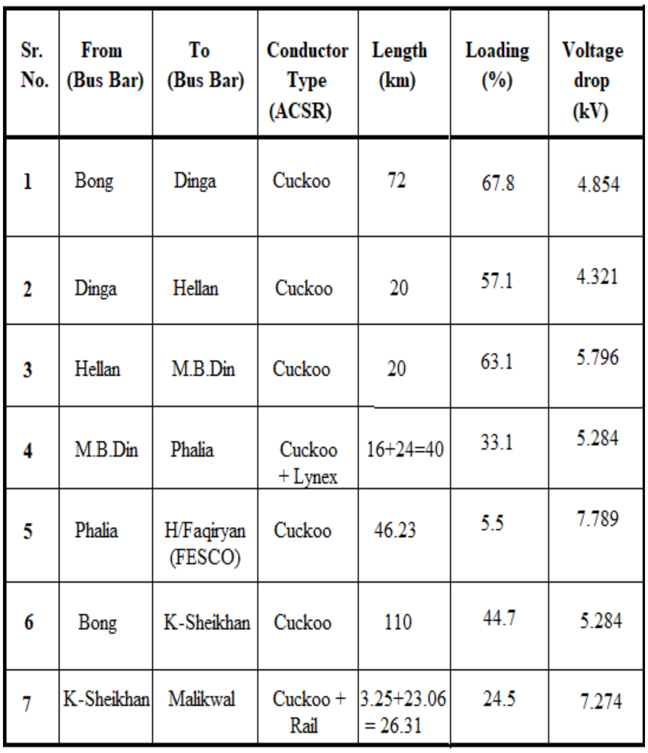
Sr. NO	Bus Name	V [kV]	P [MW]	Q [MVAR]	I [A]	θ [-deg]
1	Dinga	127.2	20.3	9.8	102	12.26
2	Hillan	127.7	27.2	9.8	137	15.21
3	MBD	126.2	34.8	13.2	177	19.25
4	Phalia	124.3	22.9	16.9	118	20.04
5	K-Sheikhan	126.7	38.7	11.1	195	12.34
6	Malikwal	124.7	16.7	7.0	84	13.63

Table 6. Feeder voltage and losses after OCP

Sr. No	Feeder	Losses (MW)	Min. Voltage (p.u)
1	F-1	6.91	0.935
2	F-2	3.182	0.928

System infeed after OCP is 199.58 MW, whereas losses are 10.09MW, and these figures before OCP were 203.09 MW and 13.6 MW, respectively. This shows that this installation has resulted in the reduction of system technical losses and system loadings conditions. Comparison of table-1, table-3, table-5, and table-6 shows that minimum feeder voltage condition is improved and considerable feeder loss reduction happened on both feeders. This comparison is also shown in Fig. 5 & 6.

Table 7. Line parameters & associated voltage drop after OCP



Sr. No.	From (Bus Bar)	To (Bus Bar)	Conductor Type (ACSR)	Length (km)	Loading (%)	Voltage drop (kV)
1	Bong	Dinga	Cuckoo	72	67.8	4.854
2	Dinga	Hellan	Cuckoo	20	57.1	4.321
3	Hellan	M.B.Din	Cuckoo	20	63.1	5.796
4	M.B.Din	Phalia	Cuckoo + Lynex	16+24=40	33.1	5.284
5	Phalia	H/Faqiryan (FESCO)	Cuckoo	46.23	5.5	7.789
6	Bong	K-Sheikhan	Cuckoo	110	44.7	5.284
7	K-Sheikhan	Malikwal	Cuckoo + Rail	3.25+23.06 = 26.31	24.5	7.274

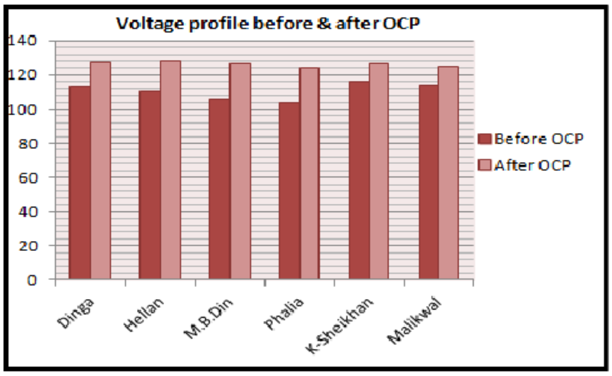


Fig. 5 Voltage comparison of GEPCO region

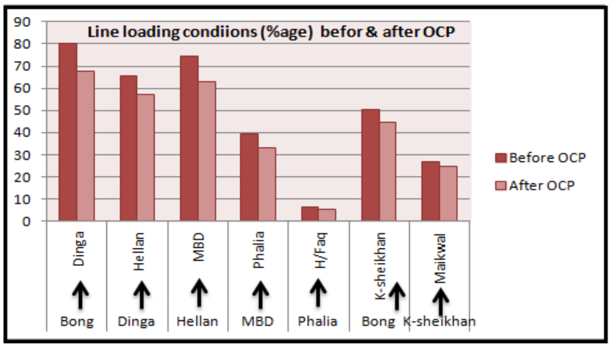


Fig. 6 Percentage line loadings before and after OCP

It is also visible from the result in Table 7. that 23% of MVA capacity is spared after OCP, as shown in Table 7. TSA considered both financial impact on the system and over compensation effect at bus bars of the whole network. Power factor of not a single bus bar is in leading situation after OCP.

VII. CONCLUSION

Results collected from actual sites and obtained from DPF are very similar, which clearly shows the methodology & algorithm opted for this work. However, capacitor installation is not the only solution for the utilities to improve the operational parameters of the network in the long run. Some recommendations to tackle these issues are there:-

- Reconfiguration of existing system and ingress of distributed generation may help in this in regard and OCP must be considered as last option.
- Utilities must review their OCP methodologies in planning & operation stages keeping in mind the ground realities.
- Modern simulation software packages are equipped with meta-heuristic optimization techniques and can help in finding optimum size, location and switching instants for better results.
- OCP is load and local network model dependent so keep an eye on these factors while designing or operating.
- Transients produced during switching of reactive power systems must be analyzed in depth to mitigate the adverse switching effects.

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