PERFORMANCE IMPROVEMENT OF GILGEL GIBIE I – MEKELLE TRANSMISSION NETWORK USING OPTIMAL PLACEMENT OF REACTIVE POWER COMPENSATORS

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ABSTRACT

This paper presents determination of optimal location, size and type of reactive power compensators for the 19 bus Ethiopian Electric Power Corporation (EEPCo) transmission network running from Gilgel Gibie to Mekelle using Genetic Algorithm (GA). The objective is to determine the optimal location and size as well as type of reactive power compensators so that the power transfer capacity and transmission efficiency of the network is maximized while keeping the bus voltages, reactive power generation/absorption at each bus and line flows within their secure limits. The efficiency of the proposed technique is demonstrated through simulation studies. The performance of the compensated network is compared with that of the uncompensated network. The proposed approach maximizes the power transfer capacity and improves the transmission efficiency as well as the voltage profile of the network as compared to that of the uncompensated network under normal loading and 50% overloading conditions. Moreover, the proposed compensation technique permits a secured 100% overloading of the transmission network whereas the uncompensated network will result in system blackout because of voltage collapse under 100% overloaded operation.

Key words: *Optimal location, reactive power compensators, genetic algorithm, transmission network, voltage profile, line flows, power transfer capacity, transmission efficiency*

INTRODUCTION

Modern high voltage transmission networks are designed to efficiently transfer the generated power to the load centers while maintaining the bus voltages close to their rated values. However, maximizing line loadability may lead to voltage collapse even though the line is operating below its thermal limit [1]. Further, in long transmission lines under low load or no load conditions, the receiving end voltage may rise above the rated value [1, 2].

The power transferring capacity and efficiency as well as the steady state voltage profile of a power system can be improved by using reactive power compensators [1, 3]. The compensators can be series compensators, shunt compensators or combination of both according to their connection to compensated transmission system. Fixed series and shunt compensators have been used for a long time to increase the power transfer capacity and improve the voltage profile of the transmission system [1]. The late introduction of power electronics based Flexible AC Transmission System (FACTS) controllers have resulted in fast and dynamic control of transmission networks [4]. This makes the AC transmission network flexible to adapt to the changing conditions caused by contingencies and load variations.

Though the compensators are commonly located either at the end or at the middle of long transmission lines, they need not to be necessarily connected in these positions of the lines [5, 6]. The optimal bus location , size and type (inductive or capacitive) of reactive power compensators can be determined by formulating and solving an optimal power flow (OPF) problem [7, 8]. The OPF problem is generally considered as the minimization of an objective function representing the generation cost and/or the transmission loss. The constraints involved are the physical laws governing the power generation-transmission systems and the operating limitations of the equipment.

Though the OPF problem has been frequently solved by using classical optimization methods, Genetic Algorithm (GA) offers a powerful approach to the solution of the OPF problems [9]. It is becoming popular because of the increasing availability of high performance computers at relatively low cost. Of late, genetic algorithm (GA) has found extensive application in solving global optimization problems where the closed form optimization technique cannot be applied. GA is a parallel and global search technique that emulates natural genetic operators and is more likely to converge toward the global solution. Moreover, this method is not sensitive to the starting point and it is capable of determining global optimum solution to the OPF problem for a range of objective functions and constrains.

This paper determines the optimal bus location, size and type (inductive or capacitive) of reactive power compensators for Gilgel Gibie I–Mekelle transmission network by solving an OPF problem using Genetic Algorithm. The reactive power compensators are proposed to be installed at the identified buses in 19 bus EEPCo transmission network running from Gilgel-Gibie I to Mekelle for maximization of power transfer capacity and transmission efficiency while keeping the bus voltages within the acceptable range, 0.9 -1.1 pu.

The selection of type of reactive power compensator is based on cost, availability and non-complexity of the controlling scheme. Taking these factors into account, Fixed Switched Shunt compensators and Static VAR Compensator (SVC) are proposed for the 19 bus EEPCo transmission network under consideration.

The effectiveness of the proposed approach is demonstrated through simulation studies. The proposed method maximizes the power transfer capacity and improves the transmission efficiency as well as the voltage profile of the network as compared to that of the uncompensated transmission network.

PROBLEM FORMULATION

The objective of this paper is to determine the optimal location, size and type (inductive or capacitive) of reactive power compensators to maximizing the power transfer capacity and improve the efficiency of the transmission network while keeping the bus voltage levels within the permissible limits. The OPF problem to achieve this objective can be written as the loss minimization on account of reactive power dispatch. Thus, the OPF problem can be written in the following form:

$$\text{Minimize Loss} = 0.5 \times \sum_{ij} (G_{ij} (|V_i|^2 + |V_j|^2 - 2|V_i V_j| \cos(\delta_j - \delta_i))) \quad (1)$$

Subject to,

$$P_{Gi} - P_{Di} = \sum_{ij} |Y_{ij} V_i V_j| \cos(\theta_{ij} + \delta_j - \delta_i) \quad (2)$$

$$Q_{Gi} - Q_{Di} = -\sum_{ij} |Y_{ij} V_i V_j| \sin(\theta_{ij} + \delta_j - \delta_i) \quad (3)$$

$$|V_i|^{\min} \le |V_i| \le |V_i|^{\max} \quad (4)$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad (5)$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (6)$$

$$|P_{ij}| \le |P_{ij}|^{\max} \quad (7)$$

where

P_{Gi} = Active power generation at bus i in pu
P_{Di} = Active power demand at bus i in pu
Q_{Gi} = Reactive power generation at bus i in pu
Q_{Di} = Reactive power demand at bus i in *pu*
$|V_i|$ = Voltage magnitude at bus i in p.u.
δ_i = Voltage angle in radians at bus i
P_{ij} = Power flow from bus i to bus j in p.u.
θ_{ij} = Phase angle of ij_{th} element of the admittance matrix in radians
$|Y_{ij}|$ = Magnitude of ij_{th} element of the admittance matrix in pu

and
$$Y_{ij} = |Y_{ij}|\cos\theta_{ij} + j|Y_{ij}|\sin\theta_{ij} = G_{ij} + jB_{ij} \quad (8)$$

where

G_{ij} = conductance of the line between bus i and bus j in pu
B_{ij} = susceptance of the line between bus i and bus j in pu

The superscripts max and min represent the maximum and the minimum limits of the corresponding variables, respectively.

The subscripts i and j vary among all buses in the power system network. Since there is no generation at load buses, for a non-generator bus i the value of P_{Gi} is zero. Consequently, Eq. (5) is not applicable for non-generator buses.

The state variables of the OPF problem are the voltage magnitude ($|V_i|$), the voltage phase angle (δ_i) as well as the output of VAR compensators (Q_{Gi}) & Q_{Gi} for non-generator buses and voltage phase angle for generator buses.

The loss minimization objective function corresponds to improving the performance of the transmission network, maximize power transfer capacity, the lines loadability and improve voltage profile.

The equality constraints are the active and the reactive power flow equations. These constraints guarantee the power balance at each node and that the total generated active and reactive power satisfy the load demand and the line losses. The inequality constraints represent the technical and/or economic restrictions of the network, the generators and the loads besides the operational limits of the VAR compensators.

The OPF problem is solved by using the Genetic Algorithm (GA) Optimization Tool of MATLAB. Brief overview of Genetic Algorithm (GA) and Genetic Algorithm Tool of MATLAB is presented as follows.

GENETIC ALGORITHM

Genetic Algorithm (GA) is a powerful stochastic search algorithm based on natural genetics and the Darwinian survival of the fittest code. GA works with a population of binary string. Without any prior knowledge of the objective function it can search several possible solutions simultaneously. GA has overcome several deficiencies of conventional numerical methods and is usually used iteratively to reach to a near global optimum solution. In each iteration (referred to as generation) of GA, a new set of strings (i.e., chromosomes) with improved fitness is produced using the genetic operators - selection, crossover and mutation as described below [5].

Selection

Selection is the process of choosing two parents from the population for crossing. It gives preference to better individuals and allows them to pass on their genes to the next generation. In the proposed GA, method of stochastic uniform selection is used for selection.

Reproduction

Reproduction is a process where the individual is selected to move to the next generation according to its fitness.

Fitness Function

The fitness function measures the quality and it is used to compare the different solutions and to select those which are fit to go to the next step (generation). The scaling function converts raw fitness scores returned by the fitness function to values in a range that is suitable for the selection function. For the proposed GA approach fitness scaling of rank is used to measure the fitness of the solutions. For OPF problem proposed for this study, the fitness function is the loss minimization.

Cross Over

Crossover is the primary genetic operator which combines two selected individuals (or parents) to form a new individual (child) for the next generation. It is the process of selecting two parents solutions and producing from them an offspring. After the selection process, the population is enriched with better individuals. A scattered crossover is applied in the proposed solution technique.

Mutation

Mutation is a secondary operator which adds a random search character to the genetic algorithm and induces a random walk through the search space. It is used to introduce some sort of artificial diversification in the population to avoid premature convergence to a local optimum. A population specifies the set of chromosomes (solutions) that are encoded in binary strings. Each chromosome binary string represents the values of the state variables (i.e., bus voltages magnitudes, phase angles and reactive power output of the VAR compensators in our case) for the required solution. In this paper, constraint dependent mutation function is implemented. The above mentioned operations of selection, crossover and mutation are repeated until the best solution is obtained.

Genetic Algorithm Tool of MATLAB

The Optimization Tool of MATLAB is a graphical user interface (GUI) that can be used to solve an optimization problem with linear and nonlinear as well as equality and inequality constraints. The Optimization Tool has two major sections: the problem setup & results and the options sections. The problem set up and results section of the GA Optimization Tool enables us to specify the problem (objective function or fitness function) and the constraints and to run the solver and view the results. The options section is used to determine the different options for the GA solver such as the types of the GA operators, the stopping criteria of the algorithm and how the results to be displayed. The selection of the options has significant effect on convergence as well as the convergence time of the algorithm. In the worst case, improper selection of the options renders the Optimization Tool not to run at all.

For the 19 bus Gilgel Gibie I to Mekelle Transmission system under study the problem and the non linear constraints are specified as different functions in different M-files. The equality constraints of power flow equations and the reactive power generation limits of the generators and the inequality constraints of the thermal limits of the transmission lines are fed to the Optimization Tool as nonlinear constraints. The voltage magnitude and phase angle inequality constraints are specified as variable bounds.

NETWORK MODEL

The 19 bus transmission network running from Gilgel Gibie I to Mekelle, shown in Fig. 1, is part of EEPCo's transmission system. It comprises of transmission lines operating at 230kV, 132kV, 66kV and 45kV. Two winding and three winding transformers are employed to change voltages from one level to another. The transmission line data in per unit (pu) are given in Table 1. The generation (pu) and load demand (pu) are provided in Table 2. The base values are taken as 300MVA and rated bus voltages (kV) for each line.

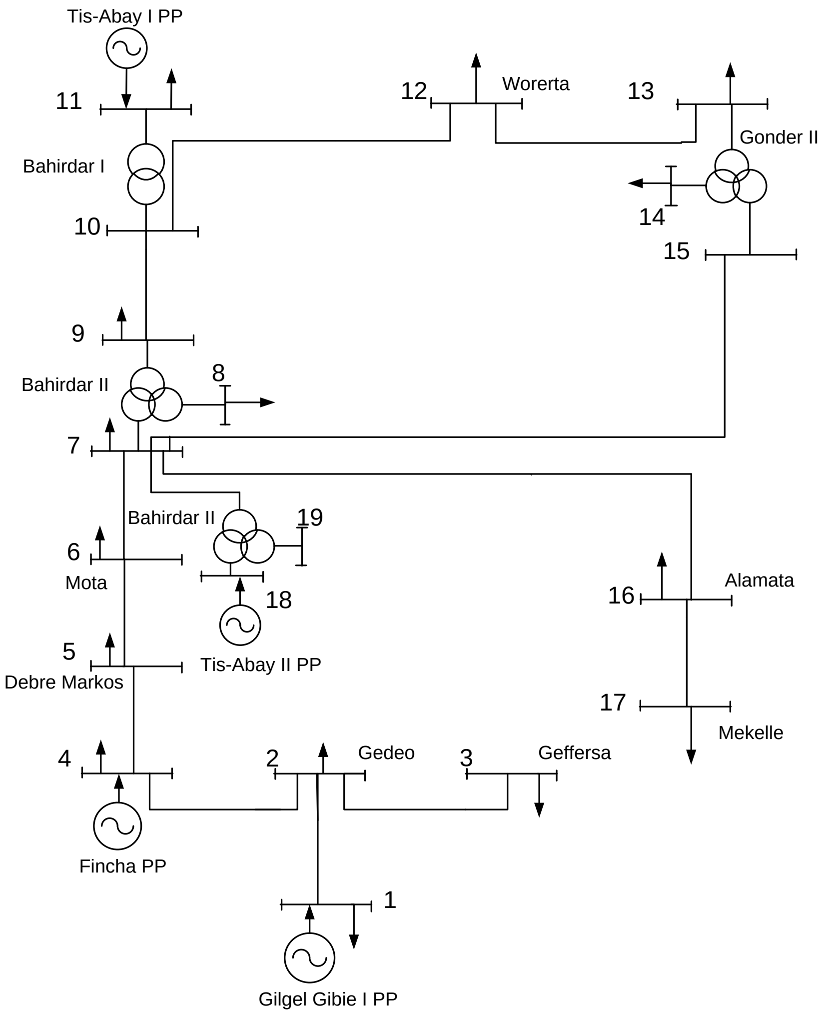


Figure 1: The 19 bus Gilgel Gibie I - Mekelle transmission network

Table 1: Transmission line data

Line No.	Node 1	Node 2	Voltage Level (kV)	Series Impedance (pu)	Series Admittance (pu)	Line Susceptance (pu)
1	Gilgel Gibie I	Gedeo	230	0.0538 + j0.3034	0.5666-j3.1955	0.06454
2	Gedeo	Geffersa	230	0.038 + j0.2417	0.6348-j4.0376	0.04814
3	Gedeo	Fincha	230	0.0256 + 0.1628	0.9426-j5.9943	0.00
4	Fincha	Debre Markos	230	0.0242+ j0.1665	0.8549-j5.8818	0.03509
5	Debre Markos	Mota	230	0.0378+0.2607j	0.5447-j3.7568	0.05502
6	Mota	Bahirdar II	230	0.0275 + j0.1892	0.7523-j5.1761	0.04003
7	Bahirdar II	Bahirdar II	230/15	66.67+ j318	0.0006-j0.003	0.00
8	Bahirdar II	Bahirdar II	230/66	0.0006 +j0.003	64.1 –j320.51	0.00
9	Bahirdar II	Bahirdar II	66/15	5.4896+ j6.814	0.0717-j0.089	0.00
10	Bahirdar II	Bahirdar I	66	0.1625+ j0.1305j	3.7411-j3.0044	0.00
11	Bhirdar I	Tis Abay I	66	0.564+ j6.999	0.0114-j0.142	0.00
12	Bhirdar I	Worta	66	1.8558+ j1.4903	0.3276-j0.2631	0.02451
13	Woreta	Gonder II	66	2.9415+j2.3622	0.2067-j0.166	0.03879
14	Gonder II	Gonder II	66/15	4.803+ j60.15	0.0013-j0.0165	0.00
15	Gonder II	Gonder II	230/66	0.582 + j9.82	0.006 –j0.1015	0.00
16	Gonder II	Gonder II	230/15	4.92+ j70.08	0.001-j0.0142	0.00
17	Gonder II	Bahirdar	230	0.0713+j0.249	1.0628-j3.7117	0.0864
18	Bahirdar II	Alamata	230	0.1763+j0.6133	0.4329-j1.5061	0.21372
19	Alamata	Mekelle	230	0.0732+j0.2548	1.0415-j3.6254	0.08887
20	Tis Abay II	Bahirdar II	138/15	6.7143+j66.7857	0.0015-j0.0148	0.00
21	Bahirdar II	Bahirdar II	230/15	6.0143+j117.9143	0.0004-j0.0085	0.00
22	Tis Abay II	Bahirdar II	230/138	0.769 + j18.476	0.0022 –j0.054	0.00

Table 2: Details of power generation and load demand

Bus Number	Bus Name	Voltage Level (kV)	Nominal Demand		Nominal Generation	
			P_D(pu)	Q_D (pu)	P_G(pu)	Q_G(pu)
1	Gilgel Gibie I	230	0.00387	0.0037	0.73	0.36357
2	Gedeo	230	0.038964	0.026196	0.00	0.00
3	Geffersa	230	0.3594	0.24156	0.00	0.00
4	Fincha	230	0.028596	0.019236	0.45917	0.14333
5	Debremarkos	230	0.0252	0.016956	0.00	0.00
6	Mota	230	0.004404	0.002964	0.00	0.00
7	Bahirdar II	230	0.00	0.00	0.00	0.00
8	Bahirdar II 15k	15	0.030396	0.020436	0.00	0.00
9	Bahirdar II 66 kV	66	0.021564	0.014436	0.00	0.00
10	Bahirda I 66 kV	66	0.00	0.00	0.00	0.00
11	Bahirdar I 45 kV	45	0.017604	0.011844	0.048	0.036
12	Woreta	66	0.00843	0.006924	0.00	0.00
13	Gonder II	66	0.010116	0.00567	0.00	0.00
14	Gonder II 15 kV	15	0.0275	0.01847	0.00	0.00
15	Gonder II 230 kV	230	0.00	0.00	0.00	0.00
16	Alamata	230	0.014076	0.009444	0.00	0.00
17	Mekelle	230	0.136884	0.092916	0.00	0.00
18	Tis Abay II	132	0.00	0.00	0.24	0.11624
19	Bahirdar II 15 kV	15	0.018	0.0121	0.00	0.00

SIMULATION RESULTS

Optimal location of reactive power compensators for the 19 bus system, shown in Fig. 1, is obtained by minimization of Eq. (1) subject to the constraints given in Eqs. (2-7).

As the 230kV lines cover a long distance and most of the power is drawn from them, the compensators are installed only on the 230kV buses. In the 19 bus system, there are 8 buses operating at 230kV voltage level. In determining the optimal location, size and type of reactive power compensators, reactive power generators with reactive power output of Q_{Gi} , i denoting the 230kV buses, are assumed to be attached to the 8 buses at 230kV level. The values of Q_{Gi} are obtained by solving the OPF problem using the Genetic Algorithm Solver of MATLAB. The transmission system analysis is carried out for the following different loading conditions:

i. Nominal loading condition

ii. 50% overloaded condition

iii. 100% overloaded condition

The Genetic Algorithm Solver of MATLAB demands the options for the different parameters that govern the optimization process and the convergence of the optimal solution to be selected. For simulation studies under three loading conditions the population size is selected to be 200 and the elite count is set to 20. The default values are taken for the other options such as Fitness scaling, Selection, Reproduction, Mutation, Crossover and Stopping criteria.

The output of the reactive power compensators to be installed at the eight 230kV buses for different loading conditions are given in Table 3. The positive sign indicates injection of reactive power to the corresponding bus using capacitive type of compensators while the negative sign represents reactive power drawn by the attached reactors from the corresponding bus. If the sign of the output of the compensators changes under different loading conditions at a given bus, a VAR compensator with inductive and capacitive nature (SVC) is proposed for that bus.

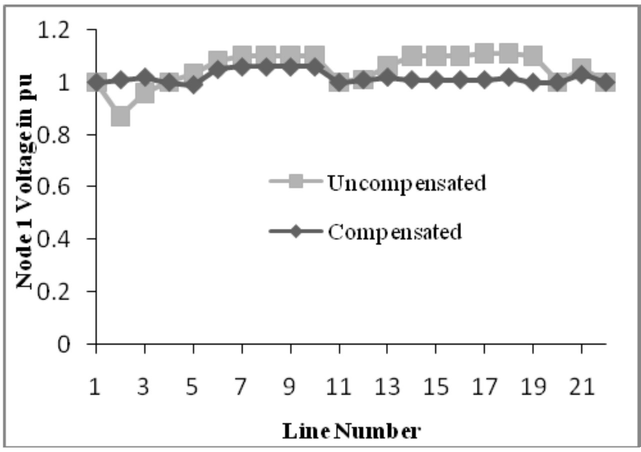
Table 3: Output of reactive power compensators under different loading conditions

230KV Bus number	Reactive power output of the compensators (MVA)		
	Nominal loading conditions	50% Overloading conditions	100% Overloading conditions
2	65	82	106
3	80	120	136
5	-81	-79	-10
6	45	49	18
7	73	76	49
15	-81	-60	-7
16	-67	-30	0
17	7	21	33

The power flow analysis of the 19 bus transmission system with and without the proposed reactive power compensators is carried out using the power flow analysis software, “Power World Simulator 8.0”, and selecting bus 1 as the system slack bus. The simulation results as obtained under the three different loading conditions are presented in Tables 4, 5, 6, and Figs. 2, 3, 4 as follows.

Table 4: Performance comparison of uncompensated and compensated networks under nominal loading conditions

Line No.	Node 1	Node 2	Uncompensated			Compensated		
			Node 1 Voltage (pu)	Line Loss (MW)	Reactive Power flow (MVR)	Node 1 Voltage (pu)	Line Loss (MW)	Reactive Power flow (MVR)
1	Gilgel Gibie I 230kV	Gedeo 230 kV	1.00	1.36	19.73	1.00	1.27	1.11
2	Geffersa 230 kV	Gedeo 230 kV	0.87	2.79	71.47	1.01	1.47	0.40
3	Gedeo 230 kV	Fincha 230 kV	0.96	0.57	37.51	1.02	0.25	66.75
4	Fincha 230 kV	Debre Markos 230 kV	1.00	0.95	70.10	1.00	0.61	6.12
5	Debre Markos 230 kV	Mota 230 kV	1.03	1.19	71.07	0.99	1.54	85.08
6	Mota 230 kV	Bahirdar II 230 kV	1.08	0.7	52.83	1.05	0.52	19.30
7	Bahirdar II 230 kV	Bahirdar II 15 kV	1.10	0.00058	6.40	1.06	0.00042	6.31
8	Bahirdar II 230 kV	Bahirdar II 66 kV	1.10	0.00039	17.37	1.06	0.00035	13.16
9	Bahirdar II 66 kV	Bahirdar II 15 kV	1.10	0.00003	0.27	1.06	0.00003	0.17
10	Bahirdar II 66 kV	Bahirdar I 66 kV	1.10	2.12	13.00	1.06	0.96	9.00
11	Tis Abay I 45 kV	Bahirdar I 66KV	1.00	0.04	29.62	1.00	0.02	20.70
12	Bhirdar I 66KV	Worta 66 kV	1.01	1.41	17.80	1.01	0.69	12.46
13	Woreta 66 kV	Gonder II 66 kV	1.06	0.5	13.81	1.02	0.12	8.23
14	Gonder II 66 kV	Gonder II 15 kV	1.10	0.00036	2.16	1.01	0.00026	1.96
15	Gonder II 66 kV	Gonder II 230 kV	1.10	0.00032	0.31	1.01	0.00013	0.06
16	Gonder II 230 kV	Gonder II 230 kV	1.10	0.00879	7.83	1.01	0.0056	3.65
17	Gonder II 230 kV	Bahirdar II 230 kV	1.11	0.03	8.13	1.01	0.88	74.18
18	Alamata 230 kV	Bahirdar II 230 kV	1.11	1.76	76.25	1.02	1.29	20.00
19	Mekelle 230 kV	Alamata 230 kV	1.10	0.37	27.87	1.00	0.42	20.81
20	Tis Abay II 132 kV	Bahirdar II 15 kV	1.00	0.07401	16.69	1.00	0.0235	9.01
21	Bahirdar II 15 kV	Bahirdar II 230 kV	1.05	0.11437	21.18	1.03	0.0514	12.60
22	Tis Abay II 132 kV	Bahirdar II 230 kV	1.00	0.00269	1.83	1.00	0.00711	1.01
	Total			13.9915	583.226		10.128	392.07



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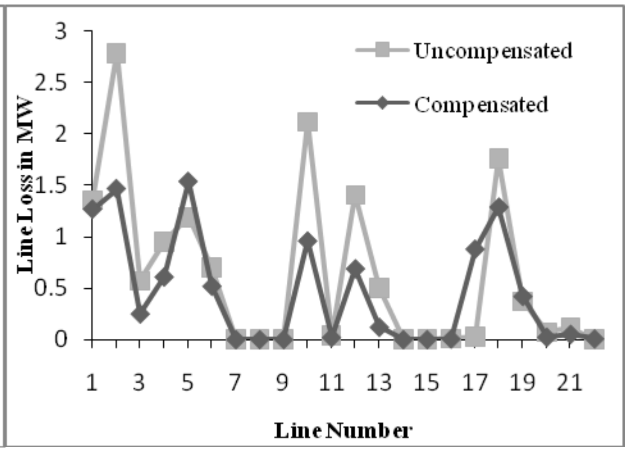

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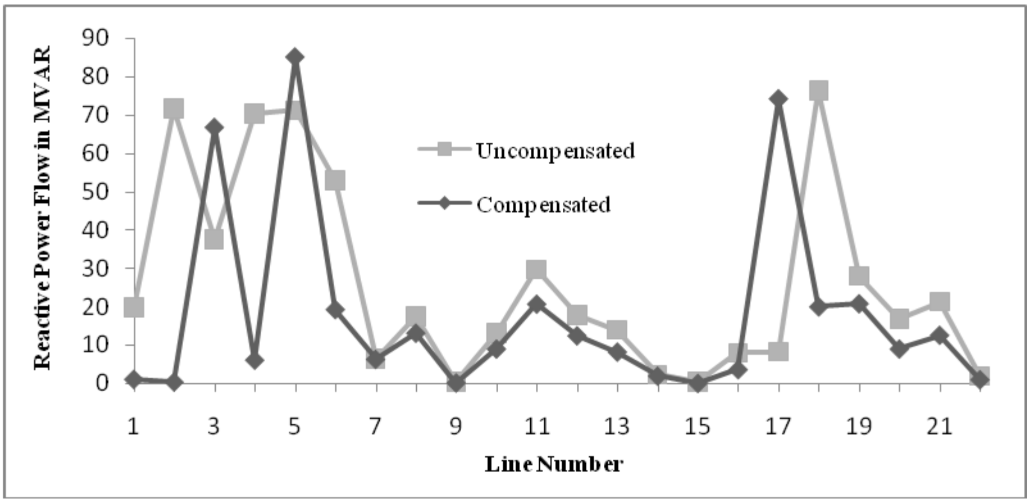


(c)

Figure 2 Performance comparison of uncompensated and compensated networks under nominal loading conditions (a) Node Voltage, (b) Line Loss and (c) Reactive Power Flow

Table 5: Performance comparison of uncompensated and compensated networks under 50% overloading conditions

Line No.	Node 1	Node 2	Uncompensated network			Compensated network		
			Node 1 Voltage (pu)	Line Loss (MW)	Reactive Power flow (MVR)	Node 1 Voltage (pu)	Line Loss (MW)	Reactive Power flow (MVR)
1	Gilgel Gibie I 230 kV	Gedeo 230 kV	1.00	8.74	58.41	1.00	7.45	29.60
2	Geffersa 230 kV	Gedeo 230 kV	0.76	8.2	107.00	0.99	3.44	12.76
3	Gedeo 230 kV	Fincha 230 kV	0.92	2.13	144.08	1.01	0.02	8.58
4	Fincha 230 kV	Debre Markos 23 kV	1.00	1.53	25.15	1.00	1.53	4.52
5	Debre Markos 230 kV	Mota 230 kV	1.00	1.98	32.80	0.99	2.72	82.09
6	Mota 230 kV	Bahirdar II 230 kV	1.01	1.33	27.68	1.04	1.28	31.82
7	Bahirdar II 230 kV	Bahirdar II 15 kV	1.02	0.00099	9.22	1.05	0.00094	9.25
8	Bahirdar II 230 kV	Bahirdar II 66 kV	1.02	0.00034	9.93	1.06	0.00043	12.04
9	Bahirdar II 66 kV	Bahirdar II 15 kV	1.02	0.00006	0.01	1.05	0.00005	0.05
10	Bahirdar II 66 kV	Bahirdar I 66 kV	1.02	0.16	3.00	1.05	0.36	6.00
11	Tis Abay I 45 kV	Bahirdar I 66 kV	1.00	0.01	13.90	1.00	0.01	15.25
12	Bhirdar I 66 kV	Worta 66 kV	1.01	0.44	10.58	1.01	0.43	9.88
13	Woreta 66 kV	Gonder II 66 kV	1.01	0.03	7.61	1.00	0.03	6.94
14	Gonder II 66 kV	Gonder II 15 kV	1.02	0.00096	1.93	1.00	0.00086	2.24
15	Gonder II 66 kV	Gonder II 230 kV	1.02	0.00065	0.15	1.00	0.00058	0.13
16	Gonder II 230 kV	Gonder II 230 kV	1.02	0.0194	6.65	1.00	0.01842	6.32
17	Gonder II 230 kV	Bahirdar II 230 kV	1.02	0.07	6.80	1.00	0.72	65.96
18	Alamata 230 kV	Bahirdar II 230 kV	0.98	2.93	33.38	1.01	2.75	30.35
19	Mekelle 230 kV	Alamata 230 kV	0.94	1.3	41.81	0.99	0.98	21.64
20	Tis Abay II 132 kV	Bahirdar II 15 kV	1.00	0.0003	0.97	1.00	0.01108	6.28
21	Bahirdar II 15 kV	Bahirdar II 230 kV	1.00	0.02567	6.01	1.02	0.0509	11.43
22	Tis Abay II 132 kV	Bahirdar II 230 kV	1.00	0.00055	0.35	1.00	0.00196	6.25
	Total			28.89892	560.91		21.80522	365.903

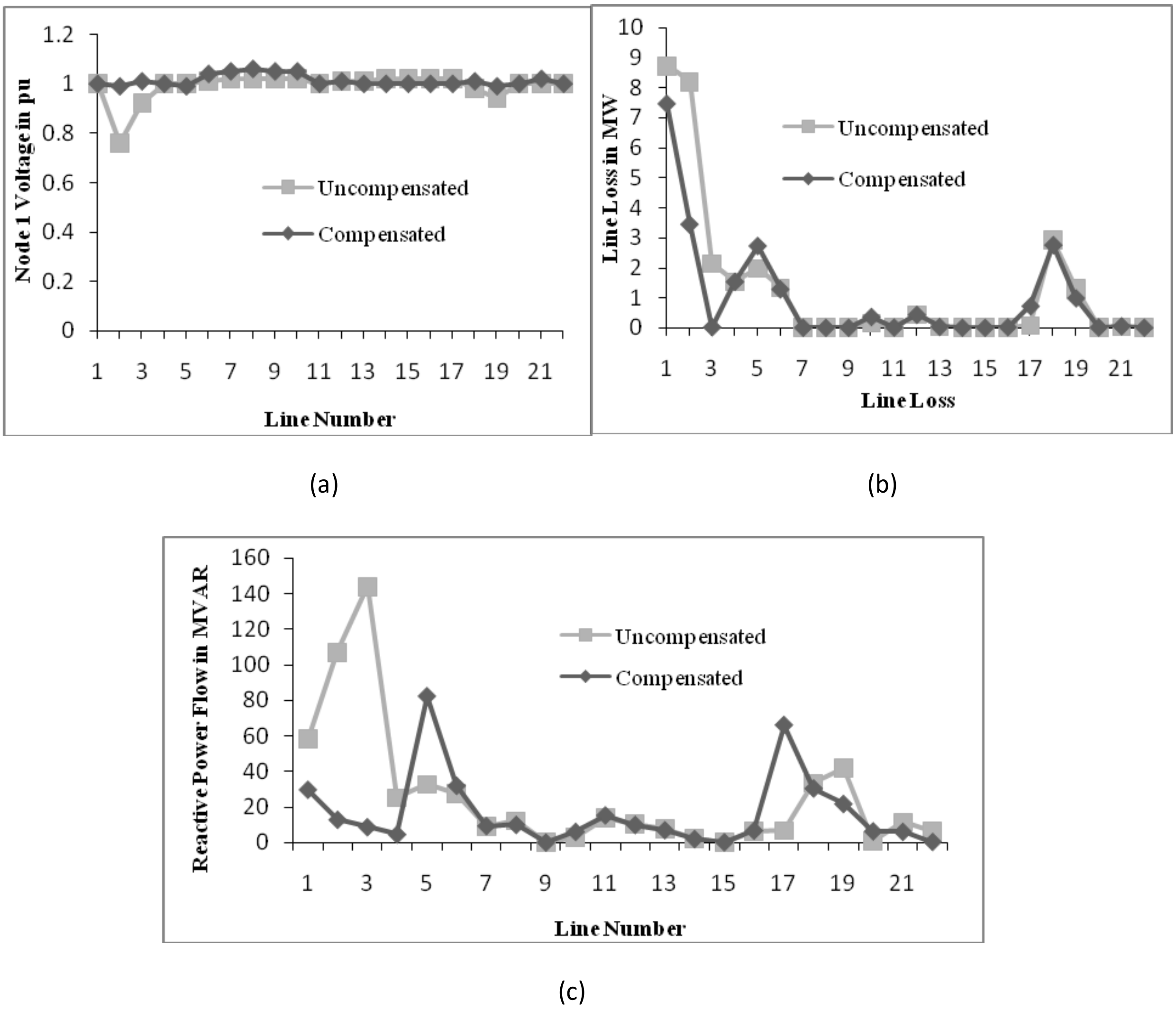
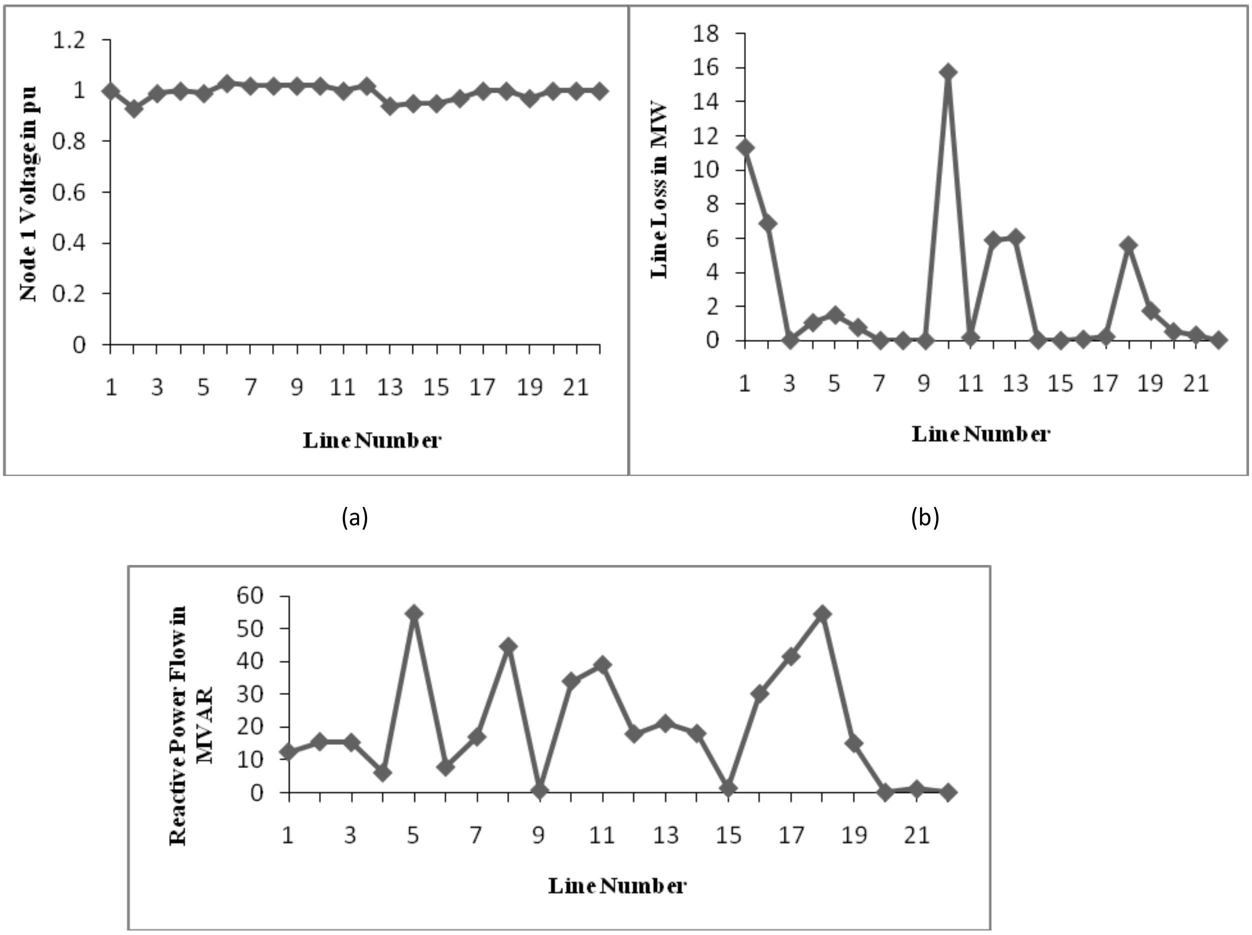


Figure 3 Performance comparison of uncompensated and compensated networks under 50% overloading conditions (a) Node Voltage, (b) Line Loss and (c) Reactive Power Flow

Table 6: Performance of the compensated network under 100 % overloading conditions

Line No	Bode 1	Node 2	Node 1 Voltage (pu)	Line Loss (MW)	Reactive Power flow (MVR)
1	Gilgel Gibie 1 230KV	Gedeo 230 kV	1.00	11.3	12.48
2	Geffersa 230KV	Gedeo 230 kV	0.93	6.86	15.60
3	Gedeo 230kV	Fincha 230 kV	0.99	0.02	15.38
4	Fincha 230kV	Debre Markos 230KV	1.00	1.05	6.15
5	Debre Markos 230KV	Mota 230 kV	0.99	1.5	54.57
6	Mota 230kV	Bahirdar II 230 kV	1.03	0.77	7.89
7	Bahirdar II 230kV kV	Bahirdar II 15 kV	1.02	0.00183	13.07
8	Bahirdar II 230k	Bahirdar II 66 kV	1.02	0.0033	44.60
9	Bahirdar II 66kv	Bahirdar II 15 kV	1.02	0.00024	0.80
10	Bahirdar II 66kv	Bahirdar I 66 kV	1.02	15.72	34.00
11	Tis Abay I 45kV	Bahirdar I 66 kV	1.00	0.18	39.02
12	Bhirdar I 66kV	Worta 66 kV	1.02	5.89	17.95
13	Woreta 66kV	Gonder II 66 kV	0.94	6.04	21.17
14	Gonder II 66kV	Gonder II 15 kV	0.95	0.02541	18.11
15	Gonder II 66kV kV kV	Gonder II 230 kV	0.95	0.00418	1.46
16	Gonder II 230KV	Gonder II 230 kV	0.97	0.07296	30.22
17	Gonder II 230KV	Bahirdar II 230 kV	1.00	0.23	41.50
18	Alamata 230kV kV kV kV	Bahirdar II 230 kV	1.00	5.59	54.47
19	Mekelle 230 kV	Alamata 230 kV	0.97	1.74	15.10
20	Tis Abay II 132KV	Bahirdar II 15 kV	1.00	0.51624	0.17
21	Bahirdar II 15KV	Bahirdar II 230 kV	1.00	0.31999	1.16
22	Tis Abay II 132KV	Bahirdar II 230 kV	1.00	0.03156	0.193
Total				57.86571	449.06



(a) (b)

(c)

Figure 4: Performance of the compensated network under 100 % overloading conditions (a) Node Voltage, (b) Line Loss and (c) Reactive Power Flow

DISCUSSION

The simulation results presented in Tables 4, 5 and 6 and illustrated in Figs. 2, 3 and 4 reveal that the uncompensated network experiences unacceptable voltage sags and swells under normal and overloaded operating conditions. It is observed that at certain buses the voltage level drops to 0.87 pu while at some other buses the voltage level rises to 1.11 pu even if the uncompensated network is operated under normal loading conditions. On the contrary, the maximum voltage variation is only 6% of the rated value under normal loading condition and 50% overloaded operating condition when the transmission network is compensated using the proposed technique. It is also observed that the maximum voltage sag at one of the buses of the uncompensated network under 50% overloading condition is 24%. It is further observed that the uncompensated transmission network under consideration will face system black out because of voltage collapse if it is operated under 100% overloaded operating conditions whereas the proposed compensation approach allows 100% overloading of the network with only a maximum of 7% voltage sag at the buses.

The reactive power flow through most of the lines of the compensated network under normal loading and overloaded operating conditions has decreased significantly as compared to the same for the uncompensated network. It is further observed that the overall transmission loss for the uncompensated network is 38% more than that of the compensated one even under nominal loading condition because of the additional loss incurred in the uncompensated system due to large reactive power flows.

A comparison of performance of the uncompensated and compensated network is presented in Table 7 given below.

Table 7: Performance comparison of uncompensated and compensated network

Operation Conditions	Attributes	Uncompensated Network	Compensated Network
Normal loading conditions	Maximum Voltage Swell	11 %	6%
	Maximum Voltage Sag	13%	1%
	Total Reactive Power Flow	543.526 MVAR	392.07 MVAR
	Overall Transmission Loss	13.99154 MW	10.12884MW
50% Overloading conditions	Maximum Voltage Swell	2%	6%
	Maximum Voltage Sag	24%	1%
	Total Reactive Power Flow	560.91 MVAR	365.93 MVAR
	Overall Transmission Loss	28.8989 MW	21.80522MW
100% Overloading conditions	Maximum Voltage Swell/Sag	Voltage Collapse	7%
	Total Reactive Power Flow		449.06 MVAR
	Overall Transmission Loss		57.8657 MW

CONCLUSIONS

Genetic Algorithm based optimal power flow solution is proposed to determine the optimal location (bus) , size and type (inductive or capacitive) of the reactive power compensators to be installed in the 19 bus Gilgel Gibie I to Mekelle EEPCo transmission sub-network .

The results presented in Table 7 reveal that the net MVAR requirement of the compensated network under normal loading and overloaded operating conditions is significantly less than the same for the uncompensated network. Further, the overall transmission loss of the uncompensated network is higher than that of the compensated one even under nominal loading condition because of the additional loss incurred in the uncompensated system due to large reactive power flows.

A comparison of performance of the uncompensated and compensated network presented in Table 7 further reveals that that the proposed reactive power compensation approach enhances the power transfer capacity and improves the transmission efficiency as well as the voltage profile of the transmission network under consideration even if it is operated under overloaded operating conditions.

Taking the cost of the different types of VAR compensators and the limited market availability of the sophisticated FACTS devices [10, 11] into consideration, the fixed switched shunt compensators and static VAR compensators are proposed for the EEPCo transmission network under study.

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