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OPTIMAL PLACEMENT AND SIZING OF HT SHUNT CAPACITORS FOR TRANSMISSION LOSS MINIMIZATION AND VOLTAGE PROFILE IMPROVEMENT: THE CASE OF RRVPNL POWER GRID

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ABSTRACT

The loss minimization and voltage stability enhancement are the important objectives in operating the transmission networks. In this paper, a method to evaluate the optimal placement and restructuring of HT Shunt Capacitors in RRVPNL Power Grid for minimization of transmission system losses and voltage profile improvement based on cost benefit analysis and PR index is proposed. The costs considered are economic cost associated with HT Shunt Capacitors. The PR index is the index of losses decrement which in the proposed algorithm is the ratio of total losses in the system after capacitor placement to all of losses before capacitor placement. The benefits from reactive power compensation are defined as the reduced generation costs due to reduced losses and reduced total system costs. The benefits are also achieved from the fact that power generation schedules can be changed by increased transmission capability in the network which will allow for more generation from cheap sources to be delivered to the load centers and more energy can be sold to the customers which would increase the sales due to higher transmission capacity. The benefits are considered in terms of cost for economic justification of investments in installation and restructuring of reactive power sources. The method is based on power flow solution iteratively using MATLAB to arrive at the optimal solution.

Keywords: Grid Sub-Station, HT Shunt Capacitor Bank, Loss Minimization, Optimal Capacitor Placement, Reactive Power Support, RRVPNL Power Grid, Transmission System, Voltage Stability.

1. INTRODUCTION

In A.C. system the fluctuation of frequency can be studied independently of the fluctuation in voltage. Variation in frequency is the result of imbalance between active power demand and generation. The voltage fluctuation is, by and large, the result of imbalance between reactive power demand and supply. The demand for reactive power arises at numerous points of power system e.g. consumer's inductive load, arc furnaces, steel rolling mills, fluorescent lighting, inductance of transformers, transmission and distribution lines, no load magnetizing current of transformers [1]. A transmission system is an interface between the generating stations and distribution systems. In transmission system, the voltages at buses reduces when moved away from the substation, also the losses are high. The reason for decrease in voltage and high losses is the insufficient amount of reactive power, which can be provided by the shunt capacitors. But the placement of the capacitor with appropriate size is always a challenge. Thus the optimal capacitor placement problem is to determine the location and size of capacitors to be placed in transmission networks in an efficient way to reduce the power losses and improve the voltage profile of the system [2]. OmPrakash Mahela *et al.* [3] presented different techniques of capacitor placement in transmission and distribution system to reduce line losses and voltage stability enhancement.

The I^2R losses can be separated to active and reactive component of current branch, where the losses produced by reactive current can be reduced by VAR compensation by the installation of shunt capacitors [4]. VAR compensation is defined as the management of reactive power to improve the performance of ac power systems. The concept of VAR compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues, since most of power quality problems can be attenuated or solved with an adequate control of reactive power. Reactive power compensation in transmission systems also improves the stability of the ac system by increasing the maximum active power that can be transmitted. It also helps to maintain a substantially flat voltage profile at all levels of power transmission, improves HVDC (High Voltage Direct Current) conversion terminal performance, increases transmission efficiency, controls steady-state and temporary over voltages, and can avoid disastrous blackouts [5]-[6].

There are many ways for capacitor placement and determination of size of capacitors in power systems. References [7]-[9] have considered capacitor placement in power networks using Genetic Algorithm for optimization, [10]-[12] have considered Particle Swarm Optimization technique, [13] has considered Plant Growth Optimization, [14] has considered the Game Theory, [15]-[16] have considered Ant Colony Optimization, [17] has presented a MATLAB based approach for optimal capacitor placement for loss reduction in radial distribution feeder and [18] has considered Body Immune Algorithm for optimal Placement of Capacitors. The current methods are useful and practical but the majority of them only considers some of the effective parameters for this problem and mostly concentrated only on capacitor placement in distribution networks.

The proposed study consider three different parameters viz. power reduction (PR) index, voltage constraints and cost function for placement and sizing of capacitors in the RRVPNL Power grid and design a restructuring model for capacitor placement. This paper is organized is organized as follows: Section II describes the proposed system of RRVPNL power grid. Section III presents optimal capacitor placement and sizing problem formulation. The proposed methodology and simulation results with their discussion are presented in sections IV and V, respectively.

2. THE PROPOSED SYSTEM OF RRVPNL POWER GRID

The RRVPNL power-grid is the power transmission network of Rajasthan state of India. Rajasthan is the largest state of India with total area 342,239 km^2 located in western region. The RRVPNL power grid supplies the large agriculture loads. High power losses are one of the serious problems in the transmission and distribution systems in Rajasthan, where power system is compensated in terms of fixed HT shunt capacitor banks. The losses in the transmission network of Rajasthan state of India was 4.86% in the year 2011-12 [19] and researches show that about 13% of the power produced in the system wastes as ohmic losses [20]. In India, collective of all states, in 2008 the technical and non technical losses are accounted as 23% of the total input energy [21]. In transmission network of RRVPNL Power Grid, the HT shunt capacitor banks of 38KV 7.2 MVAR or 33 KV, 5.43 MVAR consisting of two sections connected in parallel controlled by different isolators are used [22]. In the RRVPNL power grid the HT shunt capacitor banks are installed at the 220 KV GSS and 132 KV GSS on the 33KV voltage level based on the THUMB RULE: *"One 38 KV 7.2 MVAR or 33 KV 5.43 MVAR capacitor bank is proposed on 33KV voltage level for the 10/12.5 MVA capacity of the transformer in the RRVPNL transmission network"*. The proposed study considers that the HT shunt capacitors should not be allocated according to thumb rule rather should be placed on the basis of reactive power requirement of the system which ultimately depends on nature of load connected to the GSS. The 220 KV GSS Chomu and four 132 KV GSS viz. Rampura Dabri, Govindgarh, Markhi, and Ajitgarh which receive power from 220 KV GSS Chomu are considered in the study. The single line diagram of this system is shown in Fig. 1.

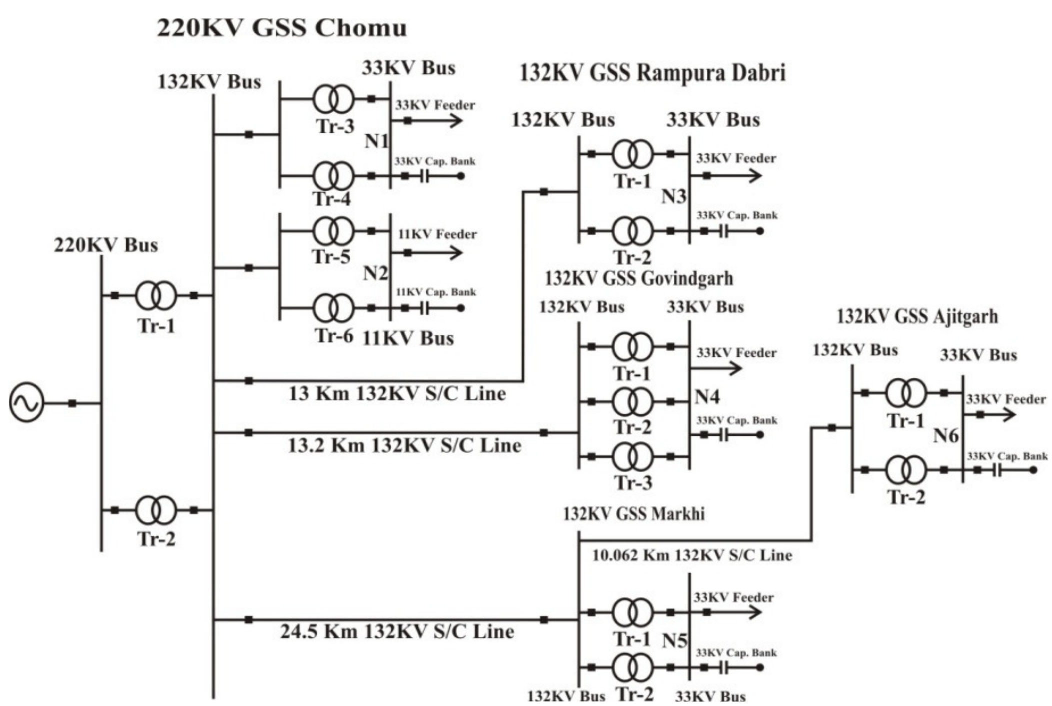

Fig. 1: Single-line diagram of proposed system

3. OPTIMAL CAPACITOR PLACEMENT AND SIZING PROBLEM FORMULATION

The objective of capacitor placement in the electric network is to minimize the losses and improve voltage profile. The main objective function is to minimize the system active power loss and improve the voltage profile and to restructure the capacitor placement in the RRVPNL power grid to optimize the use of available capacitors in the system based on cost benefit analysis. The load and capacitor model, objective function, constraints formulation, power loss calculations and power loss reduction factor are described in this section [3].

3.1 LOAD AND CAPACITOR MODEL

The loads and capacitors are modeled as impedance. The impedance model of loads and capacitors are given by Eq. (1) and Eq. (2):

$$Z_{Load_i} = R_{Load_i} + jX_{load_i} \qquad (1)$$

i = 1, 2, 3… NL

Where NL = number of loads

Z_{Load_i} = load impedance of i^{th} load

R_{Load_i} = load resistance of i^{th} load

X_{load_i} = load reactance of i^{th} load

$$Z_{C_k} = -jX_{C_k} \qquad (2)$$

k = 1, 2, 3… NC

Where NC = number of capacitors

Z_{C_k} = impedance of k^{th} capacitor

X_{C_k} = reactance of k^{th} capacitor

3.2 OBJECTIVE FUNCTION

The three-phase system is considered as balanced and loads are assumed as time invariant. Mathematically, the objective function of the problem is minimizing the loss and voltage deviation. This function is:

$$F = W_1 \times P_{loss} + W_2 \times \sum_{i=1}^{n}(1 - v_i)^2 \qquad (3)$$

Where W_1 and W_2 are objective function coefficient for power loss and objective function coefficient for voltage deviation. P_{loss} Is total loss in transmission system. v_i Is voltage magnitude of i^{th} load.

3.3 CONSTRAINTS

The voltage magnitude at each bus must be maintained within its limits and is expressed as:

$$v_{min} < |v_i| < v_{max} \qquad (4)$$

Where $|v_i|$ is voltage magnitude of i^{th} bus. v_{min} is bus minimum voltage limit. v_{max} is bus maximum voltage limit. The maximum and minimum voltages limits in the suggested model used, as per voltage limits specified by the Indian Electricity Grid Code as given in Table-1.

Table.1: Maximum and Minimum Voltage Level as Per Iegc*

Voltage-(KV rms)		
Nominal	**Maximum**	**Minimum**
765	800	728
400	420	380
220	245	198
132	145	122
110	121	99
66	72	60
33	36	30

*Source L-1/18/2010-CERC [23].

3.4 POWER LOSS CALCULATION

The complex power at the i^{th} bus is given by the relation

$$P_i - jQ_i = V_i^* I_i \tag{5}$$

Where

P_i : Load active power
Q_i : Load reactive power
V_i : Voltage at i^{th} bus
I_i : Load current at i^{th} bus

The bus voltage and line losses can be calculated by the Gauss-Seidel iterative method employing the following formula [24]:

$$V_i^{(k+1)} = \frac{1}{Y_{ii}}\left(\frac{P_i - jQ_i}{V_i^{*(k)}} - \sum_{\substack{n=1\\ n\neq i}}^{m} Y_{in}V_n\right) \tag{6}$$

Where

$V_i^{(k)}$: Voltage of bus i at the k^{th} iteration
P_i , Q_i : Bus active and reactive power of bus i
$Y_{im}= y_{i,m}$ for $i \neq m$
And $Y_{ii} = y_{i,m-1} + y_{i,m+1} + y_{ci}$ for $i = m$

The power loss in the line section between buses i and i+1, at power frequency can be computed by:

$$P_{loss(i,i+1)} = R_{i,i+1}\left[|V_{i+1} - V_i|.\,|y_{i,i+1}|\right]^2 \tag{7}$$

Where

$y_{i,i+1} = \frac{1}{(R_{i,i+1}+X_{i,i+1})}$: Admittance of the line section between buses i and i+1.
$R_{i,i+1}$: Resistance of the line connecting bus i and i+1.
$X_{i,i+1}$: Reactance of the line connecting bus i and i+1.

The total power loss is given by the relation:

$$P_{loss} = \sum_{i=0}^{mn} P_{loss(i,i+1)} \tag{8}$$

4. PROPOSED METHODOLOGY

The solution procedure for solving the problem of optimal allocation and sizing of capacitor with objective function of active power loss reduction and voltage profile improvement in electric transmission lines of RRVPNL Power Grid based on cost benefit analysis is shown in Fig. 2. First we solve the basic optimal power flow in the system using Gauss-Seidel Load Flow Method and define the candidate places for capacitor placement depending to where the highest power flow is observed in the system and then iteratively apply the HT Shunt capacitors one by one or several capacitors at the same time to different candidate places and capacitors of different capacity with different combinations. After finding the optimal solutions we compare capacity of HT shunt capacitors found by optimal solutions and existing in the system. We compare the economic cost of investment required for the shifting of HT capacitor banks and new installation as suggested by the optimal solution with the benefits of optimal capacitor placement with restructuring of capacitors. The benefits from reactive power compensation are defined as the reduced generation costs due to reduced losses and reduced total system costs. The benefits are also achieved from the fact that power generation schedules can be changed by increased transmission capability in the network which will allow for more generation from cheap sources to be delivered to the load centers and more energy can be sold to the customers which would increase the sale due to higher transmission capacity. For comparison the benefits are calculated in terms of cost. If economic cost is less than the maximum available benefits, then the solution is successful otherwise the solution is not successful.

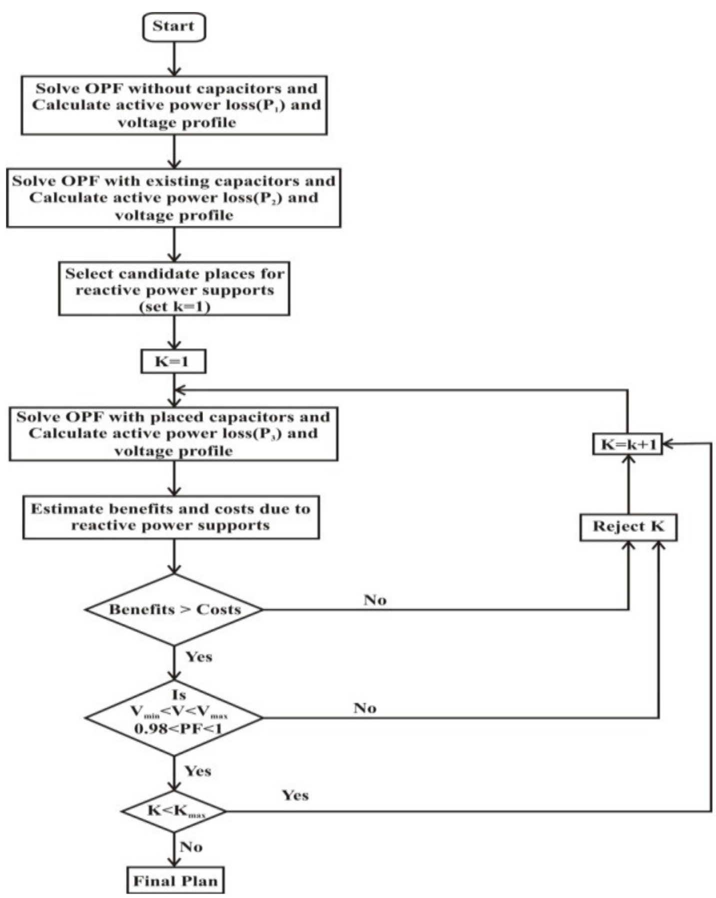

Fig. 2: Flow chart of proposed methodology

In this study, we consider Power Reduction (PR) index for estimation of loss reduction by optimal placement of capacitor banks. The PR index is the index of losses decrement which in the proposed algorithm is the ratio of total losses in the system after capacitor placement to all of losses before capacitor placement:

$$PR = \frac{P_{lossnew}}{P_{loss}}$$

Results obtained from the proposed algorithm will be as follows:

- PR < 1: Capacitor placement results in costs reduction.
- PR = 1: Capacitor placement does not have any effect on network.
- PR > 1: Capacitor placement results in costs increment.

For suggested model the PR index should be less than 1 as well as it should be less than the existing value of PR index for the grid.

5. SIMULATION RESULTS AND DISCUSSION

In the proposed study, we model a part of the RRVPNL power grid with three voltage levels of 33KV, 132KV and 220KV as shown in Fig. 1. The technical parameters of 132 KV transmission lines used to transfer power from 220KV GSS Chomu to four 132 KV GSS under study are given in Table. 2 [22]. The technical parameters of transformers installed at GSS under study are given in Table. 3 [25]. The active power, reactive power and voltage of HV and LV sides of transformer are also given in the Table. 3. The Load, Connected capacitors, total installed capacity of capacitors, power factor and voltage on the candidate buses at the time of study are shown in Table. 4.

Table.2:132 Kv Transmission Line Parameters

S. No.	Parameters of Transmission Line	Value of Parameters
1	Positive sequence reactance	1.30890E-3 H/Km
2	Zero Sequence Reactance	3.27225E-3 H/Km
3	Positive sequence Resistance	0.15850 Ω/Km
4	Zero Sequence Resistance	0.39625 Ω/Km
5	Positive sequence Resistance	9.13424E-9 F/Km
6	Zero Sequence Resistance	3.27225E-9 F/Km
7	Line length from 220 KV GSS Chomu to 132 KV GSS Rampura Dabri (S/C)	13 Km
8	Line length from 220 KV GSS Chomu to 132 KV GSS Govindgarh (S/C)	13.2 Km
9	Line length from 220 KV GSS Chomu to 132 KV GSS Markhi (S/C)	24.5 Km
10	Line length from 132 KV GSS Markhi to 132 KV GSS Ajitgarh (S/C)	10.062 Km
11	Rated Voltage	132 KV
12	Surge Impedance Loading	50MW

Table.3: Transformer Parameters

	Transformers	Rated Voltage (KV)		Nominal Power	%Impedance at Normal Tap Position	Voltage at the time of Study (KV)		Active Power	Reactive Power
		HV Side	LV Side	(MVA)		HV Side	LV Side	(MW)	(MVAR
220 KV GSS Chomu	Tr-1	220	132	160	6.89/9.18/11.48	210	133	78	35.02
	Tr-2	220	132	160	6.89/9.18/11.48	210	133	78	35.02
	Tr-3	132	33	40/50	12.59	133	34	13.087	11.55
	Tr-4	132	33	20/25	10.34	133	34	13.613	11.60
	Tr-5	132	11	10/12.5	9.94	133	11.2	2.28	0.65
	Tr-6	132	11	10/12.5	9.945	133	11.2	2.32	0.66
132 KV GSS Rampura Dabri	Tr-1	132	33	20/25	10.33	132	34	13.32	4.836
	Tr-2	132	33	20/25	10.18	132	34	13.40	4.838
132 KV GSS Govindgarh	Tr-1	132	33	20/25	9.90	127	31.89	14.30	5.403
	Tr-2	132	33	20/25	10.148	127	31.89	14.496	5.478
	Tr-3	132	33	20/25	9.32	127	31.89	14.81	5.597
132 KV GSS Markhi	Tr-1	132	33	20/25	8.09/11.11	124	31	11.70	5.399
	Tr-2	132	33	20/25	10	124	31	9.88	4.545
132 KV GSS Ajitgarh	Tr-1	132	33	20/25	9.80	130	33.5	10.28	5.23
	Tr-2	132	33	20/25	9.98	130	33.5	8.42	4.30

Table.4: Actual and Rated Parameters of Candidate Buses

Candidate Bus No.	Rated Bus Voltage (KV)	Actual Bus Voltage (KV)	Total installed Capacitors (MVAR)	Total Connected Capacitors (MVAR)	Load (Amperes)	Power Factor
N 1	33	34	15.751	8.036	453	0.930 Lag
N 2	11	11.2	5.04	2.02	410	0.990 Lag
N 3	33	34	16.290	8.145	506	0.950 Lag
N 4	33	31.89	16.290	10.86	819	0.950 Lag
N 5	33	31	10.86	8.145	420	0.906 Lag
N 6	33	33.5	10.86	5.43	374	0.937 g

5.1 Iterative Simulations for Case-I

In this case, the power flow calculations on the considered grid have been conducted without any capacitors present in the network. The active power loss, reactive power loss in the system and voltage at all the candidate places are calculated using MATLAB simulation. The active and reactive power losses are shown in Table. 6. The voltages of all candidate buses are shown in Table. 7. The power losses calculated in this case are used as reference for PR index calculation. The PR index in this case is therefore equal to 1. The cost benefits, in this case are taken as zero.

5.2 Iterative Simulations for Case-II

In this case, the power flow calculations on the considered grid have been conducted with existing capacitors in the network. The active power loss, reactive power loss in the system and voltage at all the candidate places are calculated using MATLAB simulation. The active power losses, reactive power losses, PR index and cost benefits due to installation of capacitors are shown in Table. 6. The cost benefits are calculated in terms of relative factor because the calculation in terms of currency depends on the period under consideration. The voltages of all candidate buses are shown in Table. 7.

5.3 Iterative Simulations for Case-III

In this case, the power flow calculations on the considered grid have been conducted with capacitors of different ratings at different candidate places shown in Fig. 1. Four different combinations of capacitor placement are given in Table 5 as Option-1 to Option-4. The Option-4 is the optimal capacitor placement with minimum loss of active and reactive power in the network, best voltage profile in the network and maximum cost benefit. The active power loss, reactive power loss in the system and voltage at all the candidate places are calculated using MATLAB simulation. The simulation results of candidate bus voltages in each option are shown in Table 5. The active and reactive power losses, PR Index and Cost benefit in each option are shown in Table. 6. The cost benefit are 18.67% high in optimal capacitor placement condition as compared to existing capacitors. The voltages of all candidate buses in optimal capacitor placement condition and optimal results of capacitor placement at each candidate bus are shown in Table. 7.

Table.5: Capacitors at Candidate Places and Simulation Results of Voltages

Candidate Bus No.	Option-1		Option-2		Option-3		Option-4 (Optimal)	
	KV	MVAR	KV	MVAR	KV	MVAR	KV	MVAR
N 1	32.98	0	33.01	0	34	10.86	33.73	5.43
N 2	10.73	0	10.81	0	11.5	2.02	11.01	0
N 3	31.81	0	33	5.43	34	8.145	33.50	5.43
N 4	31.09	0	31.63	5.43	32.45	10.86	33.03	13.575
N 5	31.20	5.43	31.23	5.43	32.02	8.145	32.87	10.86
N 6	31.58	5.43	31.61	5.43	32.39	5.43	33	8.145

Table.6: Simulation Results of Power Losses In System

	Active Power Loss (MW)	Reactive Power Loss (MVAR)	PR Index	Cost Benefit
Case-I (Without Capacitors)	1.63	20.40	1	0
Case-II (With Existing Capacitors)	1.60	20.36	0.98	0.405
Case-III Option-1	1.60	20.19	0.98	0.465
Case-III Option-2	1.27	16.02	0.78	3.24
Case-III Option-3	1.23	15.07	0.75	3.60
Case-III Option-4 (Optimal)	0.79	6.308	0.485	7.56

Table 7: simulation Results of Bus Voltages and Optimal Capacitors

Candidate Bus No.	Rated Bus Voltage (KV)	Bus Voltage Case-I (KV)	Bus Voltage Case-II (KV)	Bus Voltage (KV) Optimal Cap Placement	Optimal Capacitors Results (MVAR)
N 1	33	32.52	34	33.73	5.43
N 2	11	10.67	11.32	11.01	0
N 3	33	31.78	34.02	33.50	5.43
N 4	33	31.02	32	33.03	13.575
N 5	33	30.95	32.05	32.87	10.86
N 6	33	31	33	33	8.145

5.4 Final Plan of Capacitor Placement

After performing all the simulations and analyzing the simulation results we could arrive at final plan for optimal capacitor placement. The capacitors required at the particular GSS looking to 20% future load expansion, capacitors which may diverted to other places and new capacitors required are shown in the Table. 8. The standard capacitors banks installed in the RRVPNL power grid are 33KV 5.43 MVAR provided in two steps of 2.715 MVAR controlled by different isolators. Therefore the capacitor banks suggested are integral multiple of 5.43 MVAR. The suggested capacitors at 220 KV GSS Chomu are quit high against the simulation results to meet out the emergency requirement for satiability of grid in abnormal conditions.

Table.8: Final Plan of Capacitor Placement and Shifting

Name of GSS	Voltage (KV)	Optimal Capacitors Suggested	New Capacitors Suggested	Capacitors Which may be diverted
220 KV GSS Chomu	33	10.86	0	5.43
	11	5.04	0	0
132 KV GSS Rampura Dabri	33	10.86	0	5.43
132 KV GSS Govindgarh	33	16.29	0	0
132 KV GSS Markhi	33	16.29	5.43	0
132 KV GSS Ajitgarh	33	10.86	0	0

6. CONCLUSION

The reactive power optimization is a complex combinatorial optimization problem. The MATLAB simulation using Gauss-Seidel power flow method is used for optimal placement and sizing of capacitor in the electric transmission network of RRVPNL Power Grid. The capacitor placement and sizing is provided by calculation of PR Index, voltage constraints and cost benefits analysis. The objective function aims to minimize the active power loss in the network, while satisfying all the power system operation constraints. The results show that the allocation of existing capacitors in the RRVPNL power Grid under study may be restructured as suggested by final selection plan of capacitors. The skilled operation of capacitor banks results in high cost benefit as well as optimum utilization of available network. Good planning helps to ensure that capacitors are placed and operated properly.

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