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RESEARCH ARTICLE

Performance Analysis of Reactive Power Circulation Control on Extra High Voltage Transmission System Parameters

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ABSTRACT In this research paper, a real time case study on Jaipur city Extra High Voltage (EHV) system for reactive power circulation is presented. Jaipur's EHV system, consisting of 20 buses, 18 transmission lines, 10 power transformers, 6 load buses, and 2 shunt reactors, has been modelled in MATLAB Simulink. Hourly recorded system parameters are collected from the grid substations for simulation studies. A methodology is proposed based on coordinated changes of tap positions of power transformers for circulating reactive power control in EHV transmission systems. As per simulation studies, average reactive power circulation is reduced to 5.6 MVAR, reactive power circulation is reduced by 87%, network voltage at 220 kV and 132 kV voltage levels is improved, and voltage variation index is decreased, transmission losses are reduced by 0.0618%, reactive power loss is reduced by 2.23%. Proposed methodology reduces reactive power and apparent power flow on lines and transformers considerably as compared to the base case. An annual energy savings of 20.76 lac is envisaged, which corresponds to an annual cost savings of Rs 1.03 crore in the Jaipur EHV transmission system with the application of the proposed methodology.

INDEX TERMS Power flow, reactive power, tap changing transformer, transmission line loss reduction, voltage stability, extra high voltage (EHV) system.

I. INTRODUCTION

Electrical power quality has been an important problem and attracted more and more attention from power system engineers. The reformation of the electric power industry has been done in recent years by distribution network operators (DNOs) to improve their energy efficiencies, reduce costs, and maintain reliability and power quality [1]. Voltage fluctuations are expected in power system because of mismatching in power generation and load demand, also loads and currents are unpredictable. Therefore, voltage regulation (VR) is required in the transmission system operation. The main function of VR is to stabilize the steady state voltage within its standardized permissible limits [2]. A load causes wide voltage fluctuations and renders the system unsuitable for operation near the maximum load transfer level. One of the important indicators for measuring power quality is the stability of the voltage [3], [4]. By controlling the voltage directly and through reactive power flow that will affect the voltage drop, we can achieve the required voltages [5]. It has been observed that reactive power circulation is reduced by virtue of the coordinated tap position of adjacent grid sub-stations (GSS) [6], [7]. It results in an increase in transmission system efficiency and voltage with reduction of loading on lines and transformers. The equipment that is normally used for voltage stability and reactive power control is tap changing transformers and shunt capacitor injection [8]. Transformer taps and phase-shifting transformers may be the causes for circulating flows in power system [9]. Unbalanced tap ratios for transformers generates circulating MVARs. In the same manner,

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phase-shifting transformers generates circulating MWs. Out of these, the more common type of circulating flow is circulating MVARs. In case of parallel transformers, unbalanced tap ratios also cause circulating MVARs that result in reactive power flowing from higher bus voltage to lower bus voltage and thus forming a loop [10]. There is a need to study the impact of tap changing transformers on loss minimization because of the circulating power between adjoining grid substations.

In parallel connected two or more transformers, the voltage difference produced by the transformers causes a circulating current, as shown in Fig. 1. The circulating currents for each transformer are of equal magnitude and flow in opposite direction for a two-transformer substation. They are also independent of the load current. Due to inductive nature of transformer impedance, the circulating current lags the transformer voltage by 90 degrees. Generally, operators change tap ratios as per the requirements and conditions that are prevailing at a given sub-station [10]. In the current Indian power system, there is no methodology available for the change of tap position of installed transformers at adjacent GSS, which are directly interconnected through two voltage level transmission lines. Also, the impact of coordinated changes in the tap position of transformers on-grid parameters, viz., MVAR circulation, voltage profile, loading, and system losses on a real system, is not considered.

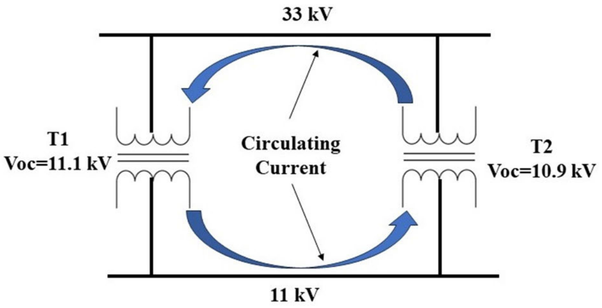

FIGURE 1. Reactive power circulation between two transformers.

Based on the above discussion, the following work has been presented in this paper:

- A methodology is proposed to change the tap position of transformers to control circulating MVAR flows in the EHV transmission system.
- A part of the Indian Power System of 20 buses consisting of 765 kV, 400 kV, 220 kV, and 132 kV voltage levels are selected for the application of the proposed methodology.
- Hourly simulation studies are carried out to assess the impact of coordinated changes in the tap position of 220/132 kV transformers on MVAR circulation, system losses, the network voltage profile, and element loading.
- The impact of unequal tap position vs equal tap position on circulating reactive power flow, transmission losses, voltage profile, line loading, and transformers has been studied and presented in the result section.

Various requisite data of transformers, transmission lines, load, and shunt reactors have been gathered from respective Jaipur GSS and modelled in MATLAB Simulink. Hourly system parameters, viz. bus-wise MW and MVAR demand and tap position of transformers, are also collected from respective GSSs. Results obtained by proposed methodology show the improvement in the system performance in terms of power flow control, reducing the losses, improve voltage profile, line loading and transformer loading.

II. PROBLEM IDENTIFICATION

In the Jaipur EHV transmission system, six 220 kV GSS are directly connected through 220 kV and through 132 kV lines, forming five loops of 220 kV and 132 kV lines. 220/132 kV transformers are installed at 220 kV GSS. Substation operators change taps on 220/132 kV transformers through OLTC to regulate 132 kV bus voltage. It has been observed that in an interconnected system, 220 kV bus voltage is decreased, and 132 kV bus voltage is increased with the increase of taps on 220/132 kV transformers, respectively, and vice versa. In the present power system operation condition, there is no coordination to change the tap position of transformers; therefore, GSS operators change the taps of transformers independently at their level. In the Jaipur EHV transmission system, the 220 kV GSS, Sitapura, and Sanganer are directly connected through 11 km 220 kV line and through the 11 km 132 kV line.

Both GSS have 220/132 kV transformers, and the load of these GSS is connected to a 132 kV bus. The connection diagram has been shown through a single-line diagram in Fig. 2. Recorded parameters at 220 kV GSS Sitapura on 15.2.2021 from 11 a.m. to 1 p.m. are shown in Table 1. Positive and negative signs indicate import and export of power, respectively, at 220 kV GSS Sitapura.

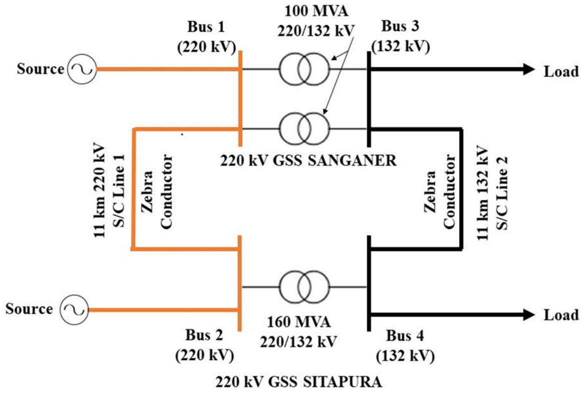

FIGURE 2. Transmission system between 220 kV GSS of Sitapura and Sanganer.

It can be observed from the table that:

i. There is no coordination between GSS operators at 220 kV GSS Sitapura and Sanganer to change the tap position of 220 kV transformers. GSS operators change the tap position of 220 kV transformers independently. Therefore,

TABLE 1. Recorded system parameters on 15.2.2021 at 220 kV GSS Sitapura.

Particulars	11 a.m.		12 p.m.		1 p.m.	
	MW	MVAR	MW	MVAR	MW	MVAR
220 kV S/C Sitapura-Sanganer Line	63	13.1	63	16.7	50	-27.3
132 kV S/C Sitapura-Sanganer Line	7	-39.1	9	-39.8	11	7.1
220 kV Transformers Tap Position at Sitapura	13		13		8	
220 kV Transformers Tap Position at Sanganer	9		9		9	
220 kV Bus Voltage at Sitapura (kV)	215.8		220.85		225	
132 kV Bus Voltage at Sitapura (kV)	130.9		134.4		133.2	
220 kV Bus Voltage at Sanganer (kV)	215.8		220.85		225	
132 kV Bus Voltage at Sanganer (kV)	130.9		134.4		133.2	
Reactive power circulation between Sitapura & Sanganer	13.1		16.7		7.1	

reactive power is being circulated from a high-potential bus to a low-potential bus, thus forming a loop.

ii. From 11 a.m. to 12 p.m., the tap position of 220 kV transformers at 220 kV GSS Sitapura is higher than at 220 kV GSS Sanganer. Therefore, 220 kV GSS Sitapura exports reactive power at 132 kV voltage level and imports it at 220 kV voltage level from 220 kV GSS Sanganer.

iii. At 1 p.m., the tap position of 220 kV transformers at 220 kV GSS Sitapura is lower than that of 220 kV GSS Sanganer. Therefore, 220 kV GSS Sitapura imports reactive power at 132 kV voltage level and exports it at 220 kV voltage level from 220 kV GSS Sanganer.

Five such loops at 220 kV and 132 kV voltage levels exist in the Jaipur EHV transmission system, as can be observed from Table 2.

TABLE 2. 220 kV and 132 kV voltage level loops in the Jaipur EHV transmission system.

Loop No.	Substation Name		Length (km)	
	From	To	220 kV Line	132 kV Line
1	220 kV GSS Sanganer	220 kV GSS Sitapura	11	11
2	220 kV GSS Sanganer	220 kV GSS Chaksu	35	35
3	220 kV GSS Sanganer	220 kV GSS Mansarovar	16	~~9~~5
4	220 kV GSS Sanganer	220 kV GSS Vatika	18	18
5	220 kV GSS Sitapura	220 kV GSS IG Nagar	9	9

It can be seen from the table that loops are forming between adjoining substations. Across this loop, MVAr flows from higher bus voltage to lower bus voltage, and therefore a significant amount of losses is incurred. As the tap ratio of the 220/132 kV transformers is not equal, reactive power is being circulated across these loops, which also results in an increase in system losses. Existing data from substations is being collected and used for analysis. The coordinated tap setting of the transformer is proposed in this work between adjoining substations to control the circulated MVAr flow and reduce losses caused by this MVAr flow.

III. TEST SYSTEM

A. TRANSMISSION LOSSES

The transmission losses of the Rajasthan power system for the last five years are shown in Table 3 [11]. From the table, it can be observed that in FY 2020–21, if transmission losses are reduced by 0.1%, then energy savings are 88.71 MUs/per annum, which is equivalent to a cost savings of Rs 44.35 crore per year. Transmission losses depend on active and reactive flow in lines and transformers and on the network voltage profile [12]. Reactive power management and voltage control in the transmission system can be used to cut down the transmission losses [13], [14].

TABLE 3. Transmission losses in the Rajasthan power system (2017 to 2021).

Year	Availability of energy (MU)	Drawl by DISCOM (including auxiliary consumption of GSS) (MU)	Transmission losses (in MU)	% Transmission losses	Cost of energy losses (@5 Rs /unit) (in Cr.)
2016-2017	73769.59	71293.29	2470.30	3.35	1235.15
2017-2018	76684.05	74102.16	2581.89	3.37	1290.94
2018-2019	81326.46	78607.08	2719.38	3.34	1359.69
2019-2020	81951.90	79219.15	2732.75	3.33	1366.38
2020-2021	81951.90	83162.11	2867.46	3.33	1433.73

B. TEST SYSTEM MODELLING

A real-time test network is considered to have a part of the Rajasthan Grid, consisting of a total of 20 buses of 765 kV, 400 kV, 220 kV, and 132 kV voltage levels. The test network initializes with a swing generator (bus-1) placed at a 765 kV voltage level at the 765 kV GSS Jaipur. It is connected to 400 kV GSS at Heerapura, Bassi, and Jaipur (PG) via 400 kV lines. Further, 220 kV GSS are connected to 400 kV GSS via 220 kV lines. Auto power transformers are installed at

765 kV, 400 kV, and 220 kV GSS. Loads are connected to 132 kV buses at 220 kV GSS. A load for Jaipur city is being met by one 765 kV GSS, three 400 kV GSS, and six 220 kV GSS EHV transmission systems. Adjacent 220 kV GSS are directly connected through 220 kV as well as 132 kV lines. 220/132 kV transformers installed at 220 kV GSS have On-load tap changers (OLTC) attached to them, which are used to change the tap position of transformers to regulate 132 kV bus voltage. Jaipur's EHV system is modelled in MATLAB Simulink. Ten grid substations that are connected with the Jaipur transmission system with different voltage levels are: 765 kV GSS Phagi, 400 kV GSS Heerapura, 400 kV GSS Bassi, 400 kV GSS Jaipur PG, 220 kV GSS Sanganer, 220 kV GSS Mansarovar, 220 kV GSS Chaksu, 220 kV GSS Vatika, 220 kV GSS Sitapura, and 220 kV GSS IG Nagar as shown in Figure 8 of the Appendix.

Table 4 presents different components connected with systems, such as the minimum and maximum values of the real and reactive loads. It also depicts the number of buses, lines, and transformers, load buses, generator buses, and shunt reactors. Information of bus voltages and line details is shown in Table 18 and Table 19 of the Appendix, respectively.

TABLE 4. Abstract of the Jaipur EHV transmission system.

SL. No	Input Data	Quantity	Data Values
1	System Real Power Load	-	maximum: 415 MW (at 11AM) minimum: 366 MW (at 5 pm)
2	System Reactive Power Load	-	maximum: 104 MVAR (at 11PM) minimum: 64 MVAR (at 11 AM)
3	Total Number of Buses	20	-
4	765 KV buses	01	-
	400 KV buses	04	-
	220 KV buses	09	-
	132 KV buses	06	-
5	Number of total lines	18	-
6	765 KV buses	03	-
	400 KV buses	10	-
	220 KV buses	05	-
7	Number of Transformers	10	
	765/400 KV Transformers	01	6000 MVA
	400/220 KV Transformers	03	3195 MVA
	220/132 KV Transformers	06	1200 MVA
8	Number of Load Buses	06	-
9	Number of Generator Buses	01	-
10	Shunt Reactors	02	25 MVAr

Positive and zero-sequence inductance and capacitance of lines are presented in Table 5. Details of different transformers are shown in Table 20 of the appendix, showing voltage ratio, rating, percentage impedance, and losses in the transformer. The voltage ratio at different taps of the 220/132 kV transformer is shown in Table 21 of the Appendix.

IV. PROPOSED METHODOLOGY

In this paper, a methodology is adopted to control the circulating MVAR in the EHV system. The methodology is based on an equal tap position of 220/132 kV transformers at adjacent 220/132 kV GSS while satisfying maximum and minimum voltage limits [15]. It has been observed that 220 kV bus voltage is decreased, whereas 132 kV bus voltage is increased, with an increase in the tap position of 220/132 kV transformers, and vice versa. The following methodology is proposed for the control of reactive power circulation in the integrated network where more than two 220 kV GSS substations are connected through 220 kV and 132 kV lines.

TABLE 5. Positive and zero-sequence inductance and capacitance of lines.

S. No.	Type of Conductor	Voltage (kV)	Line Parameters			
			Positive sequence		Zero sequence	
			Inductance (L) (H/km)	Capacitance (C) (F/km)	Inductance (L) (H/km)	Capacitance (C) (F/km)
1	Quad Moose	400	8.471e-4	1.59e-8	3.35e-3	9.19e-9
2	Twin Moose	400	1.057e-3	1.10e-8	3.949e-3	7.13e-9
3	Zebra	220	1.272e-3	9.34e-9	4.265e-3	5.86e-9
4	Panther	132	1.230e-3	9.32e-9	5.166e-3	8.39e-10

The following steps have been followed for simulation:

Step-1: Check the direction of reactive power flow on 220 kV and 132 kV lines that are directly connected to a 220 kV GSS. If the direction of reactive power flow on both lines is the same, then there is no requirement to take any action.

Step-2: If the direction of reactive power flow on 220 kV and 132 kV lines at any GSS is opposite, then the nominal tap position is set on transformers at all GSS.

Step-3: Check the limits of voltage for all buses of the GSS. If the voltage of few 132 kV buses is lower than the lower limit, then increase the tap position of the transformer at the GSS, which has the lowest 132 kV bus voltage.

Step-4: Again, check the 132 kV bus voltage for all buses. Still, if any 132 kV bus voltage is lower than the prescribed lower limit, then repeat Step 3 until the voltage of all 132 kV buses is greater than the lower limits.

Step-5: If the voltage of a few 132 kV buses is greater than the upper limit, then decrease the tap position of transformers at the GSS that have the highest 132 kV bus voltage.

Step-6: Again, check the 132 kV bus voltage for all buses. Still, if any 132 kV bus voltage is higher than the upper limit, then repeat Step 5 until the voltage of all 132 kV buses is within limits.

Step-7: If the voltage of a few 220 kV buses is lower than the lower limit, then decrease the tap position of transformers at the GSS that have the lowest 220 kV bus voltage.

Step-8: Again, check the 220 kV bus voltage for all buses. Still, if any 220 kV bus voltage is lower than the lower limit, then repeat Step 7 until the voltage of all 220 kV buses is within limits.

Step-9: If the voltage of a few of the 220 kV buses is greater than the upper limit, then increase the tap position of transformers at the GSS that have the highest 220 kV bus voltage.

Step-10: Again, check the 220 kV bus voltage for all buses. Still, if any 220 kV bus voltage is higher than the upper limit, then repeat Step 9 until the voltage of all 220 kV buses is within limits.

Step-11: Finally, check that all bus voltages are within limits. If it is not, then repeat all steps from 3 to 10.

V. OPERATIONAL PARAMETERS OF THE TEST SYSTEM

The load for Jaipur city is being met by 765 kV, 400 kV, and 220 kV GSS EHV transmission systems. Hourly recorded parameters of the six 220 kV GSS on 15.2.2021 from 11 a.m. to 5 p.m. were collected from the respective GSS and discussed in the following sections:

A. GSS LOAD

Hourly recorded power flow on 220/132 kV transformers at 220 kV GSS is tabulated in Table 6. This power flow on 220/132 kV transformers is considered a GSS load in simulation studies. Total MW and MVAR power flow at all six GSS are also presented in Table 6.

TABLE 6. Hourly recorded power flow on 220/132 kV transformers.

S. No	Name of 220 kV GSS	Recorded parameter	11 a.m.	12 Noon	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.
1	Sanganer	MW	63	59	55	55	55	56	56
		MVAR	13	11	9	19	18	25	30
2	Mansarovar	MW	78	77	70	69	68	68	67
		MVAR	6	8	6	12	12	5	5
3	Chaksu	MW	88	82	90	93	89	89	86
		MVAR	18	17	18	19	18	18	18
4	Vatika	MW	48	46	44	40	40	40	39
		MVAR	5	2	1	12	12	9	19
5	Sitapura	MW	53	53	50	53	51	50	52
		MVAR	7	8	7	8	8	7	8
6	IG Nagar	MW	85	89	72	69	67	67	66
		MVAR	15	16	25	27	26	25	24
Total System Load		MW	415	406	381	379	370	370	366
		MVAR	64	62	66	97	94	89	104

B. TAP POSITION OF 220/132 kV TRANSFORMERS

Hourly tap positions of 220/132 kV transformers installed at 220 kV GSS are shown in Table 7. This table shows that the tap positions are different between two substations that are next to each other. This causes MVAr flow to go back and forth between the two substations.

C. GSS VOLTAGE

Hourly recorded bus voltages at 220 kV GSS are presented in Table 8.

D. POWER FLOWS ON 220 kV AND 132 kV LINES

Hourly recorded power flows on 220 kV and 132 kV lines are shown in Table 9. Positive and negative signs indicate the import and export of power, respectively.

TABLE 7. Hourly recorded power flow on 220/132 kV transformers.

S. No.	Name of 220 KV GSS	Tap Position of Transformers						
		11 a.m.	12 noon	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.
1	Sanganer	9	9	9	9	9	9	9
2	Mansarovar	10	10	10	9	9	8	8
3	Chaksu	6	6	6	6	6	6	6
4	Vatika	9	9	9	7	7	7	6
5	Sitapura	13	13	8	8	8	8	8
6	IG Nagar	8	10	10	6	6	6	6

TABLE 8. Hourly recorded bus voltage (kV).

S. No.	Name of 220 kV GSS	Particulars	11 a.m.	12 noon	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.
1	Sanganer	220 kV bus	220	220	220	222	222	222	224
		132 kV bus	131	131	131	131	131	131	132
2	Mansarovar	220 kV bus	221	221	221	224	223	225	226
		132 kV bus	131	131	132	132	132	133	134
3	Chaksu	220 kV bus	224.8	219.8	225.1	225.7	225.6	226.6	227
		132 kV bus	133	131.5	132	132	132.5	133.2	133.5
4	Vatika	220 kV bus	222	223	222	227	225	226	228
		132 kV bus	132.5	132.5	132.4	132.5	132.2	132.4	132.5
5	Sitapura	220 kV bus	215.8	220.9	225	226	223.9	224.7	225.2
		132 kV bus	130.9	134.4	133.2	133.8	132.6	132.5	133.2
6	IG Nagar	220 kV bus	224.1	222.1	223.4	226.5	226	228	229
		132 kV bus	132.7	133.5	1335	132.6	131.5	132.6	133.4

E. MVAR CIRCULATION BETWEEN ADJACENT 220 kV GSS LINES

Hourly recorded reactive power circulation on 220 kV and 132 kV lines is shown in Table 10.

VI. SIMULATION RESULT AND DISCUSSION

The Jaipur EHV transmission system was looked at by recording system parameters every hour from 11 a.m. to 5 p.m. on February 15, 2021. Total seven cases have been

TABLE 9. Hourly recorded power flow on 220 kV and 132 KV lines.

S. No.	Name of Line		11 a.m.	12 noon	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.
1	220 kV S/C Sanganer-Sitapura line (Sitapura end)	MW	63	63	50	-46	44	42	40
		MVAR	13.1	16.7	-27.3	-25.5	-26.1	-26.6	-26
2	132 kV S/C Sanganer-Sitapura line (Sitapura end)	MW	7	9	11	11	13	13	15
		MVAR	-39.1	-39.8	7.1	1.4	-1.1	-1.1	-1
3	220 kV S/C Sanganer-Chaksu line (Sanganer end)	MW	-88.1	-99.3	-94.7	-93.1	-91.4	-94.0	-96.6
		MVAR	17.9	20.0	11.2	11.2	7.8	8.3	5.1
4	132 kV S/C Sanganer-Chaksu line (Sanganer end)	MW	-7.2	-9.5	-25.2	-28.3	-23.5	-21.3	-16.6
		MVAR	1.4	-22.9	-17.9	-11.6	-10.2	-6.0	-4.6
5	220 kV S/C Sanganer-Mansarovar line (Sanganer end)	MW	-27.8	-33.2	-37.6	-38.2	-37.9	-40	-42.2
		MVAR	-5.6	-9.8	-12.1	-13.6	-12.3	-6.3	-6.4
6	132 kV S/C Sanganer-Mansarovar line (Sanganer end)	MW	-1.7	-1.4	-1.3	-3.8	-4.4	-2.6	-0.2
		MVAR	-0.3	-4.5	15.8	9.1	8.9	2.4	0.9
7	220 kV S/C Sanganer-Vatika line (Vatika end)	MW	-79	-82	-84	-80	-78	-82	-80
		MVAR	-2.1	-11	-10	-15	-10	-10.3	-14.6
8	132 kV S/C Sanganer-Vatika line (Vatika end)	MW	-28	-26	-26.9	-25.5	-24	-25	-28.3
		MVAR	0	9	4	15	15.8	13	20.9
9	220 kV S/C Sitapura-IG Nagar line	MW	-18	-19	-16	-11	-8	-6	-2
		MVAR	31.9	30	20.6	25.3	26.6	31	30.5
10	132 kV S/C Sitapura-IG Nagar line		Line Opened						

TABLE 10. Hourly recorded power flow on 220 kV and 132 KV lines.

Name of Line	11 a.m.	12 Noon	1 p.m.	2 p.m.	3 p.m.	4 p.m.	5 p.m.
Reactive power circulation between 220 kV GSS Sanganer and Sitapura (Loop1)	13.1	16.7	7.1	1.4	0	0	0
Reactive power circulation between 220 kV GSS Sanganer and Chaksu (Loop2)	1.4	20.0	11.2	11.2	7.8	6.0	4.6
Reactive power circulation between 220 kV GSS Sanganer and Mansarovar (Loop3)	0	0	12.1	9.1	8.9	2.4	0.9
Reactive power circulation between 220 kV GSS Sanganer and Vatika (Loop4)	0	9	4	15	10	10.3	14.6
Reactive power circulation between 220 kV GSS Sitapura and IG Nagar (Loop5)	Loop was opened						

studied, and load flow has been performed in each case for both actual and nominal positions of tap. Abstracts of simulated cases are shown in Table 11. Load flow studies with actual tap positions (ATP) of 220/132 kV transformers are termed as "Base case" and load flow studies with nominal tap positions (NTP) of 220/132 kV transformers are termed "Proposed case".

TABLE 11. Load flow cases in Simulink for Jaipur EHV transmission system.

Case No.	Particulars of Case
Case 1A	LFS with ATP of 220/132 kV transformers at 11 a.m.
Case 1B	LFS with NTP of 220/132 kV transformers at 11 a.m.
Case 2A	LFS with ATP of 220/132 kV transformers at 12 o'clock noon
Case 2B	LFS with NTP of 220/132 kV transformers 12 o'clock noon
Case 3A	LFS with ATP of 220/132 kV transformers at 1 p.m.
Case 3B	LFS with NTP of 220/132 kV transformers at 1 p.m.
Case 4A	LFS with ATP of 220/132 kV transformers at 2 p.m.
Case 4B	LFS with NTP of 220/132 kV transformers at 2 p.m.
Case 5A	LFS with ATP of 220/132 kV transformers at 3 p.m.
Case 5B	LFS with NTP of 220/132 kV transformers at 3 p.m.
Case 6A	LFS with ATP of 220/132 kV transformers at 4 p.m.
Case 6B	LFS with NTP of 220/132 kV transformers at 4 p.m.
Case 7A	LFS with ATP of 220/132 kV transformers at 5 p.m.
Case 7B	LFS with NTP of 220/132 kV transformers at 5 p.m.

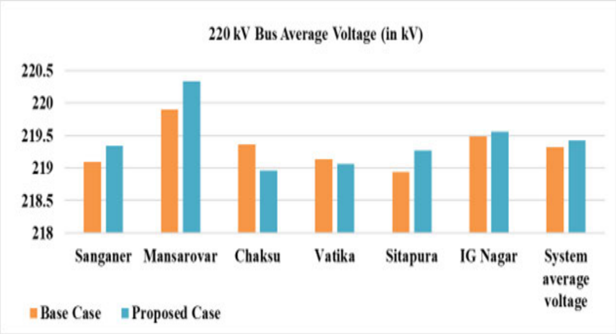

FIGURE 3. Bus average voltage of the 220 kV Jaipur EHV transmission system for the base and proposed case.

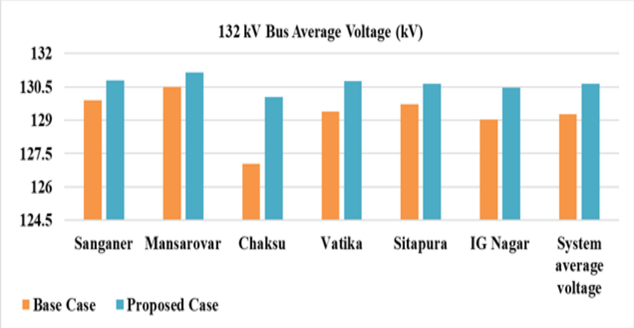

FIGURE 4. Bus average voltage of the 132 kV Jaipur EHV transmission system for the base and proposed case.

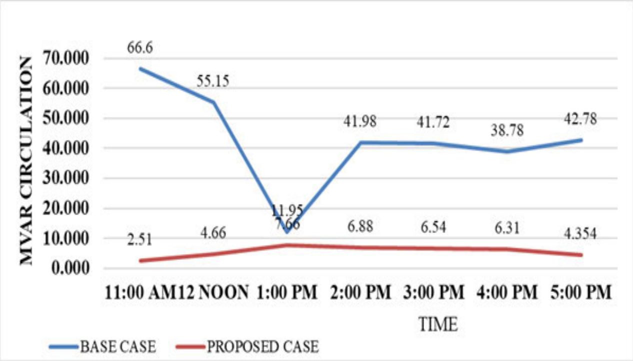

FIGURE 5. Load Comparison for reactive power circulation in the base and proposed case.

TABLE 12. Reactive power circulation in all five loops.

Particulars of case	Reduction in circulating MVAR flow	% Reduction in circulating MVAR flow
Case 1A Case 1B	64.09	96
Case 2A Case 2B	50.49	92
Case 3A Case 3B	4.29	36
Case 4A Case 4B	35.1	84
Case 5A Case 5B	35.18	84
Case 6A Case 6B	32.47	84
Case 7A Case 7B	38.426	90
Average value	37.1	87

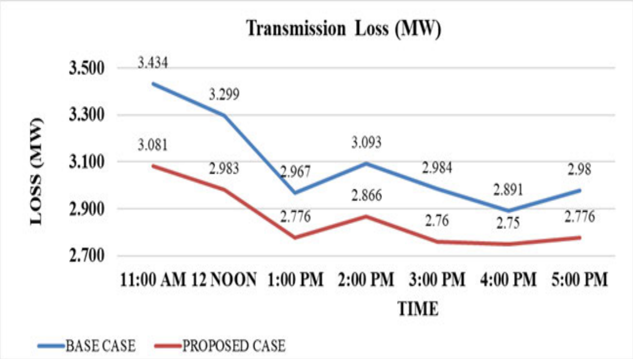

FIGURE 6. Comparison of transmission losses in the base and proposed case.

For each case, the Voltage Variation Index (VVI) is also calculated. VVI represents the degree of voltage variation from the nominal value over a specified period and is computed by using the following equation [16]:

$$\%VVT = \frac{100}{V_s} \times \frac{\sqrt{\sum_{i=1}^{N} (V_i - V_s)^2}}{N} \tag{1}$$

where, V_i = RMS value of voltage in kV at an ith hour in the period for which VVI is computed

V_s = the nominal voltage in the RMS value of the system

TABLE 13. Transmission losses in the base and proposed case.

Particulars		% Loss	Reduction in loss (MW)	Reduction in loss (%)	System load (MW)
Case 1A		0.8274	0.353	10.28	415
Case 1B		0.7424			
Case 2A		0.8126	0.316	9.58	406
Case 2B		0.7346			
Case 3A		0.7787	0.191	6.44	381
Case 3B		0.7285			
Case 4A		0.8161	0.227	7.34	379
Case 4B		0.7561			
Case 5A		0.8065	0.224	7.51	370
Case 5B		0.7460			
Case 6A		0.7814	0.141	4.88	370
Case 6B		0.7432			
Case 7A		0.8141	0.204	6.85	366
Case 7B		0.7585			
Average Value	Base case	0.8075	0.237	7.65	383
	Proposed case	0.7457			

TABLE 14. Energy savings in the proposed case as compared to the base case.

Particulars of Cases	Energy loss (kWh)	Energy saving in proposed case (kWh)
Case 1A	3434	353
Case 1B	3081	
Case 2A	3299	316
Case 2B	2983	
Case 3A	2967	191
Case 3B	2776	
Case 4A	3093	227
Case 4B	2866	
Case 5A	2984	224
Case 5B	2760	
Case 6A	2891	141
Case 6B	2750	
Case 7A	2980	204
Case 7B	2776	
Base case (average value)	3093	237
Proposed case (average value)	2856	

N = number of hourly measurements over the specified period

Detailed simulation results are explained in the following sections:

A. IMPACT ON VOLTAGE

The 220 kV and 132 kV bus voltages at 220 kV GSS for the base and proposed cases are compared and presented in Table 22 of the Appendix for all six GSS.

The average bus voltage for each bus is calculated from the values of voltages in all seven load flow cases. A comparison for the 220 kV bus and 132 kV bus average voltages of the Jaipur EHV transmission system is shown in Fig. 3 and Fig. 4 for the base case and proposed case, respectively.

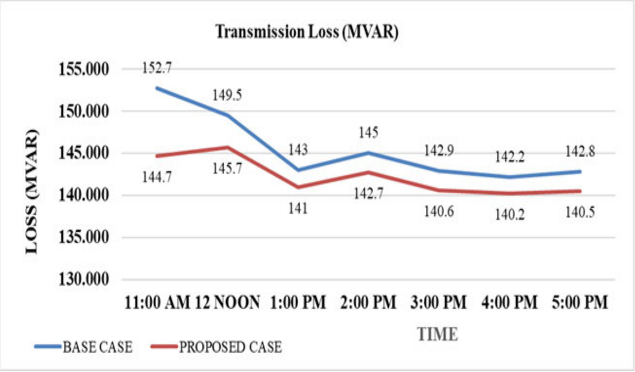

FIGURE 7. Comparison of reactive power loss in base and proposed case.

TABLE 15. Energy reactive power loss.

Particulars of Cases	Reactive loss (MVAR)	Reduction in loss (MVAR)	Reduction in loss (%)
Case 1A	152.7	8	5.24
Case 1B	144.7		
Case 2A	149.5	3.8	2.54
Case 2B	145.7		
Case 3A	143.0	2	1.40
Case 3B	141.0		
Case 4A	145	2.3	1.59
Case 4B	142.7		
Case 5A	142.9	2.3	1.61
Case 5B	140.6		
Case 6A	142.2	2	1.41
Case 6B	140.2		
Case 7A	142.8	2.3	1.61
Case 7B	140.5		
Base case (average value)	145.4	3.2	2.23
Proposed case (average value)	142.2		

A significant improvement in VVI for the proposed case can be observed. In the case of the 132 kV bus, a drastic reduction in VVI can be seen, going from 2.59% in the base case to 0.66% in the proposed case.

It can be observed from the above analysis that

i. With the increased tap position of the 220/132 kV transformer, the 220 kV bus voltage is decreased, and the 132 kV bus voltage is increased.

ii. With the decrease in tap position of 220/132 kV transformers, 220 kV bus voltage is increased, and 132 kV bus voltage is decreased.

iii. System average 220 kV Grid voltage in the proposed case increased to 219.42 kV as compared to 219.32 kV in the base case.

iv. System average 132 kV Grid voltage in the proposed case increased to 130.64 kV as compared to 129.26 kV in the base case.

v. The average 220 kV VVI in the base and proposed cases are the same. Average 132 kV VVI in the proposed case is decreased to 0.66 % as compared to 2.59 % in the base case.

TABLE 16. Average MVAR flow on lines and transformers.

Particulars	MVAR flow		MVA flow	
	Base Case	Proposed Case	Base Case	Proposed Case
220 kV S/C Sanganer-Sitapura Line	12.48	4.21	12.64	4.33
220 kV S/C Sanganer-Chaksu Line	4.22	5.80	14.70	13.90
220 kV S/C Sanganer-Mansarovar Line	20.83	26.56	48.56	52.82
220 kV S/C Sanganer-Vatika Line	4.10	7.13	4.18	7.42
220 kV S/C Sitapura-IG Nagar Line	26.24	8.23	54.06	47.42
Total (220 kV line)	**67.86**	**51.93**	**134.14**	**125.90**
132 kV S/C Sanganer-Sitapura Line	19.22	2.77	21.47	9.87
132 kV S/C Sanganer-Chaksu Line	22.06	3.16	29.23	17.24
132 kV S/C Sanganer-Mansarovar Line	29.25	13.92	41.91	30.82
132 kV S/C Sanganer-Vatika Line	9.29	2.03	9.31	2.19
132 kV S/C Sitapura-IG Nagar Line	24.82	5.38	25.63	7.64
Total (132 kV line)	**104.63**	**27.27**	**127.54**	**67.76**
200 MVA, 220/132 kV Transformer at Sanganer	25.68	12.12	62.05	56.55
160 MVA, 220/132 kV Transformer at Chaksu	6.88	16.74	69.51	73.24
160 MVA, 220/132 kV Transformer at Mansarovar	40.67	24.74	109.06	101.67
160 MVA, 220/132 kV Transformer at Vatika	1.75	8.17	42.14	43.95
200 MVA, 220/132 kV Transformer at IG Nagar	9.87	19.30	67.98	70.90
160 MVA, 220/132 kV Transformer at Sitapura	32.21	11.51	58.32	50.14
Total (220/132 kV Transformers)	**117.06**	**92.58**	**409.06**	**396.44**

TABLE 17. Comparison of MW flow and power factor for lines and transformers.

Particulars	MW flow		Power Factor	
	Base Case	Proposed Case	Base Case	Proposed Case
220 kV S/C Sanganer-Sitapura Line	2.01	1.04	0.159	0.239
220 kV S/C Sanganer-Chaksu Line	14.08	12.64	0.958	0.909
220 kV S/C Sanganer-Mansarovar Line	43.87	45.66	0.903	0.864
220 kV S/C Sanganer-Vatika Line	0.80	2.07	0.192	0.279
220 kV S/C Sitapura-IG Nagar Line	47.26	46.70	0.874	0.985
Total (220 kV line)	**108.03**	**108.11**	**0.617**	**0.655**
132 kV S/C Sanganer-Sitapura Line	9.57	9.47	0.446	0.960
132 kV S/C Sanganer-Chaksu Line	19.18	16.95	0.656	0.983
132 kV S/C Sanganer-Mansarovar Line	30.02	27.49	0.716	0.892
132 kV S/C Sanganer-Vatika Line	0.51	0.83	0.055	0.376
132 kV S/C Sitapura-IG Nagar Line	6.40	5.42	0.250	0.709
Total (132 kV line)	**65.67**	**60.16**	**0.425**	**0.784**
200 MVA, 220/132 kV Transformer at Sanganer	56.49	55.24	0.910	0.977
160 MVA, 220/132 kV Transformer at Chaksu	69.17	71.30	0.995	0.974
160 MVA, 220/132 kV Transformer at Mansarovar	101.19	98.62	0.928	0.970
160 MVA, 220/132 kV Transformer at Vatika	42.10	43.18	0.999	0.983
200 MVA, 220/132 kV Transformer at IG Nagar	67.26	68.22	0.989	0.962
160 MVA, 220/132 kV Transformer at Sitapura	48.62	48.80	0.834	0.973
Total (220/132 kV Transformers)	**384.83**	**385.35**	**0.943**	**0.973**

VVI in the base case is exceeding the limits prescribed by Rajasthan Electricity Regulatory Commission (RERC) [12].

vi. In all proposed cases, the voltage of all buses is within the limit of ± 3% of the nominal voltage, whereas in a few base cases there is a deviation in voltage from ± 3%.

B. IMPACT ON CIRCULATING REACTIVE POWER FLOW

The reactive power circulation in all five loops for the base and proposed cases is tabulated in Table 23 of the Appendix. Total reactive power circulation in all five loops for the base and the proposed case is calculated. A comparison of MVAR circulation for the base and the proposed case is shown in Fig. 5, and consolidated results are presented in Table 12. It can be observed from the above analysis that

i. With an equal tap position of 220/132 kV transformers, the difference between the 220 and 132 kV bus voltages of adjacent 220 kV GSS is decreased. Therefore, reactive power circulation is reduced in the proposed case.

ii. Reactive power flow on lines is proportional to the difference in bus voltages; therefore, reactive power circulation on 220 kV and 132 kV lines is reduced in the proposed case as compared to the base case.

iii. Average reactive power circulation among 220 kV and 132 kV networks in the proposed case is reduced to 5.6 MVAR as compared to 42.7 MVAR in the base case. Therefore, there is a reduction of 87% (37.1 MVAR) in the circulating MVAR flow.

C. IMPACT ON POWER LOSS

1) IMPACT ON MW LOSS

Transmission losses in the base and proposed cases are compared in Fig. 6, and consolidated results are presented in Table 13. It can be observed from the above analysis that

TABLE 18. Bus data in Simulink model of Jaipur EHV transmission system.

S. No.	Bus identification	Base voltage (kV)
1	bus_1 (765 kV bus at 765 kV GSS Phagi)	765
2	bus_2 (400kv bus at 765 kV GSS Phagi)	400
3.	bus_3 (400 kV bus at 400 kV GSS Heerapura)	400
4.	bus_4 (400 kV bus at 400 kV GSS Bassi)	400
5.	bus_5 (400 kV bus at 400 kV GSS Jaipur PG)	400
6.	bus_6 (220 kV bus at 400 kV GSS Heerapura)	220
7.	bus_7 (220 kV bus at 400 kV GSS Bassi)	220
8.	bus_8 (220 kV bus at 400 kV GSS Jaipur PG)	220
9.	bus_9 (220 kV bus at 220 kV GSS Sanganer)	220
10.	bus_10 (220 kV bus at 220 kV GSS Mansarovar)	220
11.	bus_11 (220 kV bus at 220 kV GSS Chaksu)	220
12.	bus_12 (220 kV bus at 220 kV GSS Vatika)	220
13.	bus_13 (220 kV bus at 220 kV GSS Sitapura)	220
14.	bus_14 (220 kV bus at 220 kV GSS IG Nagar)	220
15.	bus_15 (220 kV bus at 132 kV GSS Sanganer)	132
16.	bus_16 (132 kV bus at 220 kV GSS Mansarovar)	132
17.	bus_17 (132 kV bus at 220 kV GSS Chaksu)	132
18.	bus_18 (132 kV bus at 220 kV GSS Vatika)	132
19.	bus_19(132kv bus at 220 kV GSS Sitapura)	132
20.	bus_20 (132 kV bus at 220 kV GSS IG Nagar)	132

i. In the proposed case, average transmission loss is reduced to 2.856 MW as compared to 3.093 MW in the base case. Average transmission loss is reduced by 237 kW.

ii. In the proposed case, average transmission losses are reduced by 7.65% as compared to the base case. The maximum reduction in transmission loss is 10.28 % at 11 a.m.

iii. Average transmission losses in the proposed case are 0.7457 % as compared to 0.8075% in the base case. Losses are reduced by 0.0618%.

2) ENERGY SAVING

Energy savings in the proposed case as compared to the base case are shown in Table 14. From the simulation study, it is observed that in the proposed case, average hourly energy loss was reduced to 2856 kWh as compared to 3093 kWh in the base case. The average hourly energy saving is 237 units. Annual cost savings with the obtained simulation results can be calculated as follows:

- Average hourly cost savings = No. of units saved * per unit tariff = 237 * 5 = Rs 1185/hour
- Annual energy savings (AES) = 237 * 8760 = 20, 76, 120 kWh
- Annual cost savings = 20,76,120 * 5 = Rs 1, 03, 80,600.00

TABLE 19. Line data in Simulink model of Jaipur EHV transmission system.

S. No.	Name of line	Line length (km)	Line conductor
1	400 kV S/C Phagi-Heerapura line	52	Twin Moose
2	400 kV S/C Phagi-Bassi line	48	Quad Moose
3	400 kV S/C Bassi-Jaipur PG line	37	Quad Moose
4	220 kV S/C Sanganer-Mansarovar line	16	Zebra
5	220 kV S/C Sanganer-Chaksu line	35	Zebra
6	220 kV S/C Sanganer-Vatika line	18	Zebra
7	220 kV S/C Sanganer-Sitapura line	11	Zebra
8	220 kV S/C Sitapura –IG Nagar line	9	Zebra
9	220 kV S/C Heerapura-Mansarovar line	5	Zebra
10	220 kV S/C Jaipur PG-Chaksu line	8	Zebra
11	220 kV S/C Jaipur PG-Vatika line	28	Zebra
12	220 kV S/C Heerapura-IG Nagar line	36	Zebra
13	220 kV S/C Bassi-IG Nagar line	28	Zebra
14	132 kV S/C Sanganer-Mansarovar line	5	Panther
15	132 kV S/C Sanganer-Chaksu line	35	Zebra
16	132 kV S/C Sanganer-Vatika line	18	Panther
17	132 kV S/C Sanganer-Sitapura line	11	Zebra
18	132 kV S/C Sitapura –IG Nagar line	9	Zebra

3) IMPACT ON POWER LOSS

Reactive power losses in the base and proposed cases are compared in Fig. 7, and consolidated results are presented in Table 15.

It can be observed from the above analysis that

- In the proposed case, average reactive power loss is reduced to 142.2 MVAR as compared to 145.4 MVAR in the base case. The average loss is reduced by 3.2 MVAR.
- In the proposed case, average reactive power loss is reduced by 2.23%.

4) IMPACT ON MVAR AND MVA FLOWS ON LINES AND TRANSFORMERS

Average MVAR and MVA flow on lines and transformers in the base and proposed case is calculated from the output values of seven load flow study cases and is presented in Table 16. It can be observed from this table that:

i. Average total reactive power flow on 220 kV lines is reduced to 51.93 MVAR in the proposed case as compared to 67.86 MVAR in the base case. Reactive power flow on 220 kV lines is reduced by 23.49% in the proposed case as compared to the base case.

TABLE 20. Transformer data in the Simulink model of the Jaipur EHV transmission system.

S. No	Name of GSS	Voltage Ratio (kV)	Rating (MVA)	% Impedance	Transformer loss (kw)	PU loss
1	765/400 kV GSS Phagi	765/400	3000	14	3240	0.00108
2	400/220 kV GSS Heerapura	400/220	1065	12	1725	0.00162
3	400/220 kV GSS Bassi	400/220	1130	12	1655	0.001655
4	400/220 kV GSS Jaipur PG	400/220	1000	12	1210	0.00121
5	220/132 kV GSS Sanganer	220/132	200	10	350	0.00175
6	220/132 kV GSS Mansarovar	220/132	320	10	472	0.001475
7	220/132 kV GSS Chaksu	220/132	160	10	236	0.001475
8	220/132 kV GSS Vatika	220/132	160	10	236	0.001475
9	220/132 kV GSS Sitapura	220/132	160	10	236	0.001475
10	220/132 kV GSS IG Nagar	220/132	200	10	350	0.00175

TABLE 21. Voltage ratio at different taps of a 220/132 kV transformer in the Simulink model.

Transformer Parameters			Model of Transformer in Simulink		
Tap No.	Voltage ratio (kV)	Per tap voltage variation (pu)	Tap No.	Voltage ratio (kV)	Per tap voltage variation (pu)
1	242/132	0.0125	8	242/132	0.0125
2	239.25//132	0.0125	7	239.25//132	0.0125
3	236.5//132	0.0125	6	236.5//132	0.0125
4	233.75//132	0.0125	5	233.75//132	0.0125
5	231//132	0.0125	4	231//132	0.0125
6	228.25//132	0.0125	3	228.25//132	0.0125
7	225.5//132	0.0125	2	225.5//132	0.0125
8	222.75//132	0.0125	1	222.75//132	0.0125
9	220/132	0.0125	0	220/132	0.0125
10	217.3/132	0.0125	-1	217.3/132	0.0125
11	214.5/132	0.0125	-2	214.5/132	0.0125
12	211.8/132	0.0125	-3	211.8/132	0.0125
13	209/132	0.0125	-4	209/132	0.0125
14	206.3/132	0.0125	-5	206.3/132	0.0125
15	203.5/132	0.0125	-6	203.5/132	0.0125
16	200.8/132	0.0125	-7	200.8/132	0.0125
17	198/132	0.0125	-8	198/132	0.0125

ii. Average total reactive power flow on 132 kV lines is reduced to 27.27 MVAR in the proposed case as compared to 104.63 MVAR in the base case. Reactive power flow on 132 kV lines is reduced by 73.94%.

iii. Average total reactive power flow on 220 kV transformers is reduced to 92.58 MVAR in the proposed case as

TABLE 22. 220 kV and 132 kV bus voltages at 220 kV GSS.

GSS	Time	Tap position in base case	Tap position in proposed case	Voltage in base case (kV)		Voltage in proposed case (kV)	
				220 kV bus	132 kV bus	220 kV bus	132 kV bus
Sanganer	11 AM	9	9	219.5	131.7	219.8	131.3
	12 noon	9	9	219.8	132.3	220	131.4
	1 PM	9	9	220.1	131.5	220	131.4
	2 PM	9	9	218.5	128.7	218.8	130.3
	3 PM	9	9	218.7	128.8	219	130.5
	4 PM	9	9	218.8	128.5	219.2	130.6
	5 PM	9	9	218.2	127.7	218.6	130.1
	Average voltage	-	-	**219.09**	**129.89**	**219.34**	**130.80**
	%VVI	-	-	**0.51**	**2.07**	**0.39**	**0.59**
Mansarovar	11 AM	10	9	220.3	132.3	220.8	131.6
	12 noon	10	9	220.5	132.7	220.9	131.7
	1 PM	10	9	220.5	132.1	221	131.8
	2 PM	9	9	219.3	129.4	219.8	130.7
	3 PM	9	9	219.5	129.5	220	130.8
	4 PM	8	9	219.9	129	220.2	131
	5 PM	8	9	219.3	128.4	219.6	130.5
	Average voltage	-	-	**219.90**	**130.49**	**220.33**	**131.16**
	%VVI	-	-	**0.23**	**1.71**	**0.28**	**0.44**
Chaksu	11 AM	6	9	219.9	128	219.4	130.4
	12 noon	6	9	220.2	128.5	219.6	130.6
	1 PM	6	9	220.2	128	219.6	130.5
	2 PM	6	9	218.8	126.3	218.4	129.6
	3 PM	6	9	218.9	126.4	218.6	129.8
	4 PM	6	9	219	126.3	218.8	129.9
	5 PM	6	9	218.5	125.8	218.3	129.5
	Average voltage	-	-	**219.36**	**127.04**	**218.96**	**130.04**
	%VVI	-	-	**0.42**	**3.83**	**0.53**	**0.91**
Vatika	11 AM	9	9	219.5	131.5	219.6	131.3
	12 noon	9	9	219.9	132.1	219.7	131.5
	1 PM	9	9	219.9	131.6	219.8	131.5
	2 PM	7	9	218.6	128.0	218.5	130.2
	3 PM	7	9	218.8	128.1	218.7	130.4
	4 PM	7	9	218.8	128	218.9	130.6
	5 PM	6	9	218.4	126.5	218.2	129.8
	Average voltage	-	-	**219.13**	**129.40**	**219.06**	**130.76**
	%VVI	-	-	**0.48**	**2.53**	**0.51**	**0.63**
Sitapura	11 AM	13	9	218.9	132.5	219.8	131.1
	12 noon	13	9	219.1	133.4	219.9	131.2
	1 PM	8	9	220	131.1	220	131.2
	2 PM	8	9	218.6	127.9	218.7	130.2
	3 PM	8	9	218.8	128	218.9	130.3
	4 PM	8	9	218.9	127.9	219.1	130.5
	5 PM	8	9	218.3	127.3	218.5	130
	Average voltage	-	-	**218.94**	**129.73**	**219.27**	**130.64**
	%VVI	-	-	**0.53**	**2.48**	**0.42**	**0.65**
IG Nagar	11 AM	8	9	219.8	131.4	220	131

TABLE 22. ***(Continued.)*** **220 kV and 132 kV bus voltages at 220 kV GSS.**

12 noon	10	9	219.6	133	220.2	131.1
1 PM	10	9	220	131.3	220.2	130.9
2 PM	6	9	219.2	126.9	219	129.9
3 PM	6	9	219.4	127.1	219.2	130.1
4 PM	6	9	219.5	127	219.4	130.3
5 PM	6	9	218.9	126.6	218.9	129.9
Average voltage	-	-	**219.49**	**129.04**	**219.56**	**130.46**
%VVI	-	-	**0.28**	**2.95**	**0.31**	**0.74**

TABLE 23. **Voltage difference vs. reactive power circulation in different loops.**

Loop No.	Particulars of case	Diff. of 220 kV Transformers Tap	Diff. of 220 kV voltage (kV)	Diff. of 132 kV voltage (kV)	MVAR Circulation
Loop -1	Case 1A	-4	0.6	-0.8	23
	Case 1B	0	0	0.2	0
	Case 2A	-4	0.7	-1.1	33.65
	Case 2B	0	0.1	0.2	0
	Case 3A	1	0.1	0.4	0
	Case 3B	0	0	0.2	0
	Case 4A	1	-0.1	0.8	7.04
	Case 4B	0	0.1	0.1	0
	Case 5A	1	-0.1	0.8	7.18
	Case 5B	0	0.1	0.2	0
	Case 6A	1	-0.1	0.6	5.99
	Case 6B	0	0.1	0.1	0
	Case 7A	1	-0.1	0.4	5.67
	Case 7B	0	0.1	0.1	0.19
Loop -2	Case 1A	3	-0.4	3.7	5.44
	Case 1B	0	0.4	0.9	0
	Case 2A	3	-0.4	3.8	5.64
	Case 2B	0	0.4	0.8	0
	Case 3A	3	-0.1	3.5	2.07
	Case 3B	0	0.4	0.9	0
	Case 4A	3	-0.3	2.4	4.18
	Case 4B	0	0.4	0.7	0
	Case 5A	3	-0.2	2.4	4.17
	Case 5B	0	0.4	0.7	0
	Case 6A	3	-0.2	2.2	2.97
	Case 6B	0	0.4	0.7	0
	Case 7A	3	-0.3	1.9	4.49
	Case 7B	0	0.3	0.6	0
Loop -3	Case 1A	-1	-0.8	-0.6	0
	Case 1B	0	-1	-0.3	0
	Case 2A	-1	-0.7	-0.4	0
	Case 2B	0	-0.9	-0.3	0
	Case 3A	-1	-0.4	-0.6	0
	Case 3B	0	-1	-0.4	0
	Case 4A	0	-0.8	-0.7	0
	Case 4B	0	-1	-0.4	0
	Case 5A	0	-0.8	-0.7	0
	Case 5B	0	-1	-0.3	0
	Case 6A	1	-1.1	-0.5	0
	Case 6B	0	-1	-0.4	0
	Case 7A	1	-1.1	-0.7	0
	Case 7B	0	-1	-0.4	0
Loop -4	Case 1A	0	0	0.2	2.34
	Case 1B	0	0.2	0	0.19
	Case 2A	0	-0.1	0.2	3.79
	Case 2B	0	0.3	-0.1	1.82
	Case 3A	0	0.2	-0.1	1.70
	Case 3B	0	0.2	-0.1	2.49
	Case 4A	2	-0.1	0.7	5.04
	Case 4B	0	0.3	0.1	0
	Case 5A	2	-0.1	0.7	4.96
	Case 5B	0	0.3	0.1	0
	Case 6A	2	0	0.5	3.23
	Case 6B	0	0.3	0	0
	Case 7A	3	-0.2	1.2	7.16
	Case 7B	0	0.4	0.3	0
Loop -5	Case 1A	5	-0.9	1.1	35.82
	Case 1B	0	-0.2	0.1	2.31
	Case 2A	3	-0.5	0.4	12.06
	Case 2B	0	-0.3	0.1	2.83
	Case 3A	-2	0	-0.2	8.15
	Case 3B	0	-0.2	0.3	5.16
	Case 4A	2	-0.6	1.0	25.67
	Case 4B	0	-0.3	0.3	6.88
	Case 5A	2	-0.6	0.9	25.41
	Case 5B	0	-0.3	0.2	6.54
	Case 6A	2	-0.6	0.9	26.58
	Case 6B	0	-0.3	0.2	6.31
	Case 7A	2	-0.6	0.7	25.45
	Case 7B	0	-0.4	0.1	4.16

TABLE 23. ***(Continued.)*** **Voltage difference vs. reactive power circulation in different loops.**

compared to 117.06 MVAR in the base case. Reactive power flow on 220 kV transformers is reduced by 20.91 %.

iv. The average total MVA flow on 220 kV lines is reduced to 134.14 MVA in the proposed case as compared to 125.90 MVA in the base case. MVA flow on 220 kV lines is reduced by 6.14%.

v. The average total MVA flow on 132 kV lines is reduced to 67.76 MVA in the proposed case as compared to 127.54 MVA in the base case. MVA flow on 132 kV lines is reduced by 46.88 %.

vi. The average total MVA flow on 220 kV transformers is reduced to 396.44 MVA in the proposed case as compared to 409.06 MVA in the base case. MVA flow on 220 kV transformers is reduced by 3.08 %.

5) IMPACT ON REAL POWER FLOW AND POWER FACTOR OF LINES AND TRANSFORMERS

The average real power flow and power factor of lines and transformers are compared in Table 17 for the base and proposed case. It is calculated from the output values of seven load flow studies. It can be observed from this table that

i. There is a marginal change in MW flow on lines and transformers.

ii. The average power factor of 132 kV lines improved to 0.784 in the proposed case as compared to 0.425 in the base case.

iii. The average power factor of 220 kV lines improved to 0.655 in the proposed case as compared to 0.617 in the base case.

iv. The average power factor of 220 kV transformers improved to 0.973 in the proposed case as compared to 0.943 in the base case.

VII. CONCLUSION

This paper has presented a methodology based on coordinated changes of tap positions of power transformers for

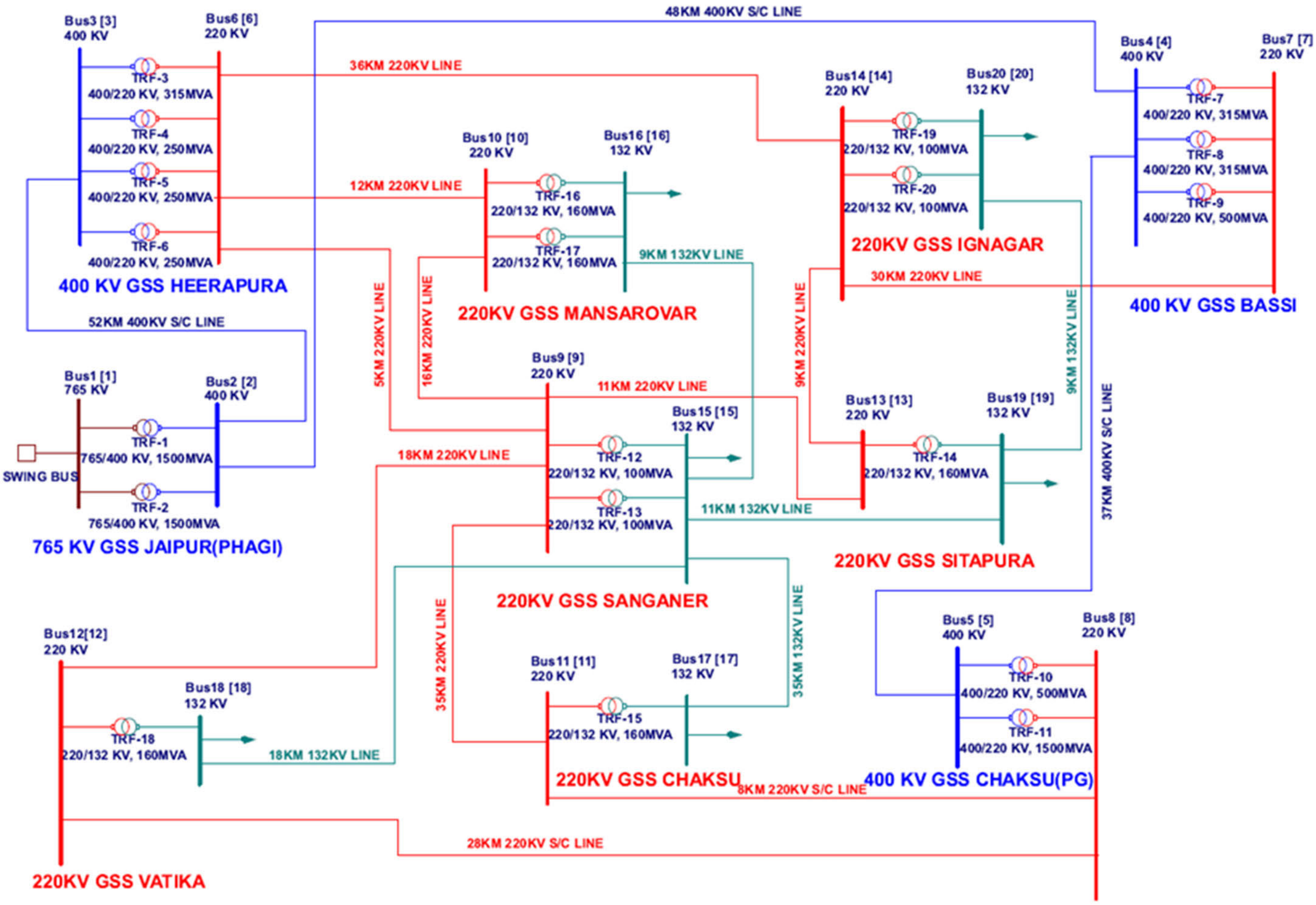

FIGURE 8. Single line diagram of Jaipur EHV transmission system.

circulating reactive power control in EHV transmission systems. A Simulink model of 20 Indian bus power systems consisting of four voltage levels (viz., 765 kV, 400 kV, 220 kV, and 132 kV) is developed to carry out simulation studies to assess the impact of circulating reactive power flow on system parameters with the application of the proposed methodology. Average reactive power circulation among 220 kV and 132 kV networks in the proposed case is reduced to 5.6 MVAR as compared to 42.7 MVAR in the base case. Reactive power circulation is reduced by 87%. The network voltage at 220 kV and 132 kV voltage levels is improved, and the 132 kV voltage variation index is decreased to 0.66% as compared to 2.59% in the base case. Transmission losses in the proposed case are reduced by 0.0618%. Annual energy savings of 20.76 lacs units are envisaged, which corresponds to an annual cost savings of Rs 1.03 crore in the Jaipur EHV transmission system with the application of the proposed methodology. Reactive power loss is reduced to 142.2 MVAR as compared to 145.4 MVAR in the base case. Reactive power loss is reduced by 2.23%. Reactive power and apparent power flow on lines and transformers are considerably reduced in the proposed case as compared to the base case, and the power factor of lines and transformers is also improved. With coordinated tap position of adjacent GSS reactive power circulation is reduced which results in an increase in transmission system efficiency, better voltage, reduce loading of lines and transformers.

APPENDIX

See Tables 18–23 and Figure 8.

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