Energy Audit of a 400/220 kV Substation – a Case Study

Sunil M. Jaralikar and Mangalpady Aruna

Abstract-- **The paper highlights the necessity of undertaking performance analysis and energy audit study of an electrical installation, more particularly a power substation on regular basis. A 630 MVA, 400/220 kV substation was identified and a detailed study was carried out to assess the various station performance parameters under different operating conditions. It was observed that the installed capacity of the station (transformer) was very large compared to the actual load it had to supply. Thus the station was under loaded and underutilized for the major period of its operation. This reduced the operational efficiency of the station. Secondly the incoming line voltage level was remaining high during most of the period of operation. Presently voltage is tried to be maintained by switching ON the line reactors at the receiving and sending ends of this station, switching OFF one of the 400 kV incoming lines during off peak loading conditions, thus risking the supply reliability. The present study emphasizes on the urgent need for improving the power quality, streamlining and optimizing the station capacity, operations and its loading pattern. Accordingly suggestions are proposed for the same.**

Index Terms-- **Bus reactor, Energy audit, Extra High Voltage (EHV) substation, Performance analysis, Station efficiency, Transformer efficiency, Power quality, Technical and commercial viability.**

I. Introduction

ELECTRICAL power is a critically important component affecting productivity, standard of living, prosperity and strength of any nation. Hence the requirement of electrical power has increased manifolds, but the power generation capacity has not been able to cope up with the demand creating an acute electrical power shortage. This is mainly due to slow rate of increase in power generation, energy pilferages due to large theft of power and transmission and distribution (T&D) losses, scarcity of the conventional sources of energy generation, poor utilization of non conventional (renewable) energy sources, speedy increase in the population and its living standards, wastage of power due to the lack of awareness towards energy conservation etc. These reasons, combined with the degradation of power quality have further deteriorated the power shortage, which if not bridged immediately may go out of control.

The power shortage could be tackled by adopting following techniques [2], [3]:

a. Increasing the power generation capacities.
b. Maintaining a qualitative power supply which is reliable, free from harmonics, and maintained within permissible voltage, power factor and frequency tolerances.
c. Undertaking the performance analysis of the electrical installations and improving their energy efficiency and also adopting energy conservation techniques.

Among the techniques suggested above, the last one is simpler, effective, environment friendly and most economical. However it necessitates planning the use of electric power in the most judicious way such that the energy usage as well as its wastage is minimized. For this, an effective scientific methodology and a tool like Energy Audit needs to be adopted [11].

With the above objectives, performance analysis using the methodology of energy audit was carried out for an Extra High Voltage (EHV) 400/220 kV substation installed and operated in the state of Goa, by a leading company involved in power transmission and distribution.

II. Technical Details of Substation

The brief technical details of the EHV substation are as follows:

- Bus bar scheme: a) 1.5 circuit breaker (for 400 kV systems). (b) 2 main and 1 transfer bus (for 220 kV system)
- No. of bays: a) 400 kV - 8, (b) 220 kV—8.
- No. of transmission lines: a) 400kV – 2. (b) 220 kV – 4.
- Extra bays under provision: 1 bay of 400 kV.
- Power transformers: 2 Nos. (315 MVA each).
- Bus-reactor (shunt): 1 No. (50 MVAr).

Transformer Details: Make-BHEL; Phases-3; Frequency-50 hertz; Type of cooling-OFAF; Line current HV-454.6A; Line current IV-826.6A, Line current LV-1837.0A, No load voltage ratio HV/IV/LV-400/220/33 kV, No. of taps-17, Percentage impedance-12.5, No load loss-101.4 kW, Load loss-274.1 kW, No load current-0.06A, Vector group-YN, a0, d11; HV winding resistance-0.2388Ω, IV winding resistance-0.2936Ω, LV winding resistance- 37.3790Ω.

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Bus Reactor Details: Make-BHEL, Phases-3, Frequency - 50 hertz, Rated power MVAr-50, Rated voltage-420 kV, Type of cooling-ONAN, Connection symbol-YN, Rated current-68.73A, Impedance /phase:-3528Ω (+0, -5 % TOL).

This substation is fed through two 400 kV lines of approximate length 150 km. The power carrying capacity of each line is about 650MVA so that in case of emergency and requirement, even one line can take care of the loading of the two installed transformers each of capacity 315MVA. Both the incoming lines are connected to two 400 kV buses which are normally coupled through a bus coupler. Also provision is already made for bringing an extra (third) line whenever need arises, thus increasing the total station power input capacity to 1950MVA. Also there is a provision for installation of a third transformer of 315MVA, increasing station output capacity to 945MVA. Presently there are four 220 kV outgoing lines and there is provision for installation of more 220 kV lines as per load requirement. The lengths of existing 220 kV lines are in the range of 40 km to 8 km. The single line diagram of the substation is as shown in Fig. 1 below.

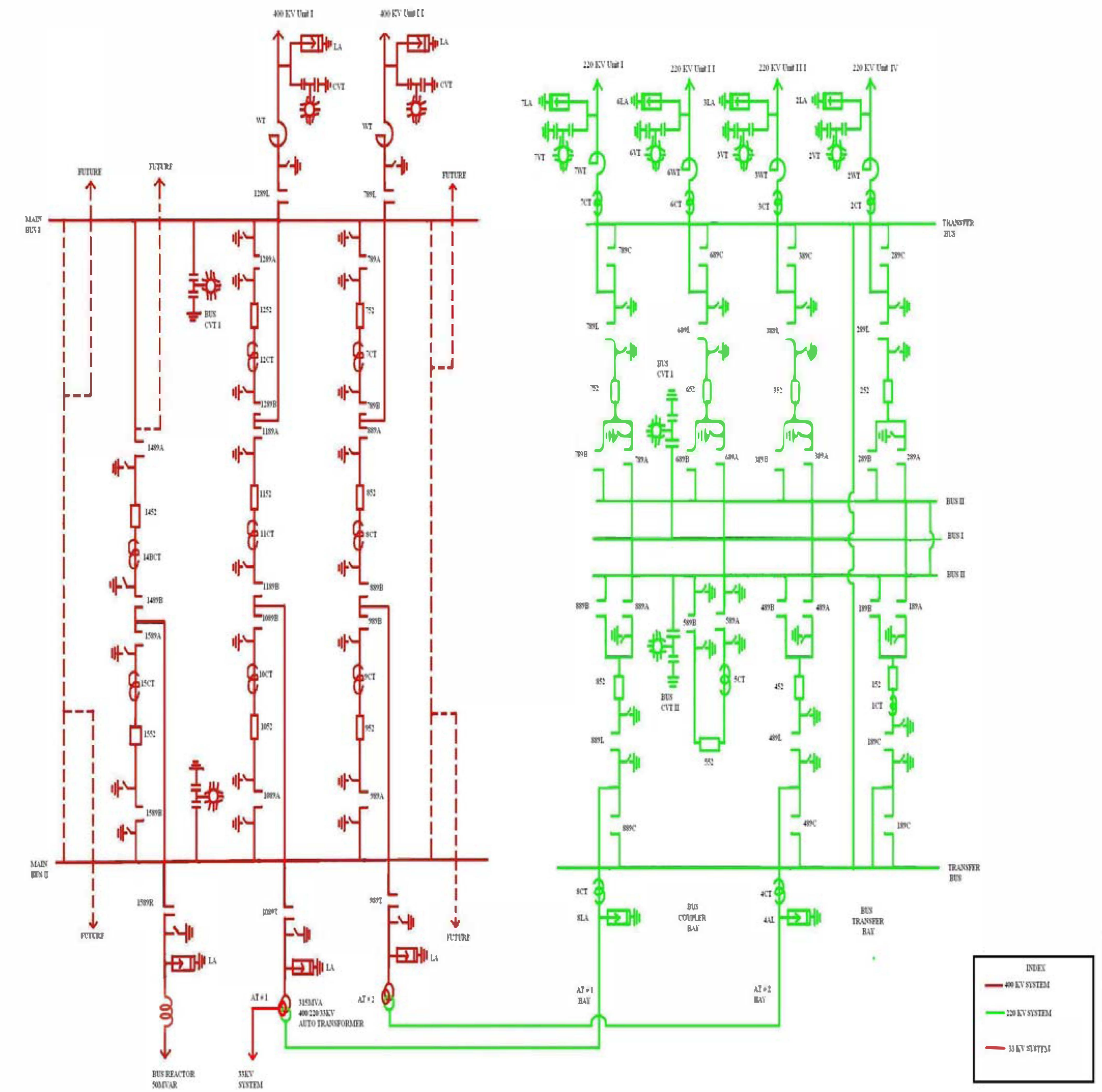

Fig. 1. Single Line Diagram of the EHV Substation.

III. Performance Analysis

The power transfer and performance details of the station are logged in an automatic data logger on hourly and four hourly intervals. The data of the transformers, bus reactor, incoming and outgoing lines etc. was collected. The sample data logging of the same is given in Table 1 and Table 2. The various performance parameters such as power factor (P.F), station loading, transformer load loss, station efficiency, transformer efficiency and loading at which transformer efficiency is maximum, are calculated [10]. The results of the analysis are as given in Table 3 and are represented graphically, as shown in Fig. 2 below.

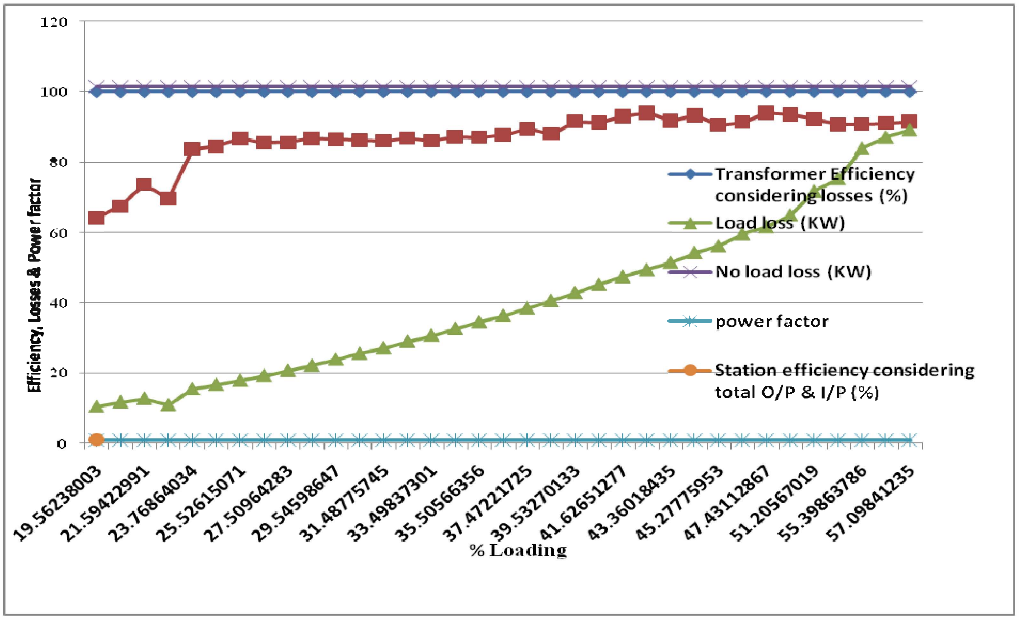

Fig. 2. Graph of Station Performance Analysis.

From the above graph it is observed that there is a large mismatch in the values of station efficiency and actual transformer efficiency, which in the ideal condition should have been nearly the same. The station efficiency has been calculated using input-output (direct) method wherein station input and output (in MVA) under various loading conditions was considered. However the transformer efficiency has been calculated using indirect or losses method wherein the actual transformer loading (in MW) and the losses have been considered.

IV. Results and Observations

From the observed field data and results obtained by calculations the following observations have been made:

1) The input voltage varies widely between 435 kV to 390 kV with 50MVAr bus shunt reactor is in OFF condition and reduces to 420 kV with the 50MVAr bus shunt reactor is in ON condition.
2) For reducing the level of incoming voltage, one 50MVAr shunt bus reactor is installed at this station and one line reactor of capacity 80MVAr is installed at the sending station end. However, in spite of this the voltage level reaches up to 420 kV which is still on the higher side compared to the rated incoming voltage level. Hence, almost every day during light loads, particularly in the night hours, one of the 400 kV incoming lines is forced to be tripped, as a last attempt to control the incoming voltage rise.
3) The output voltage varies between 232 kV to 220 kV.
4) Frequency varies between 49 to 50.5 hertz.
5) Both the transformers are kept in ON condition continuously and being operated in parallel, they share the load equally.
6) Loading of each transformer normally varies in the wide range between 19 to 60%. The transformers are loaded near to 60% only during the peak periods of loading, which are generally of small duration. Hence, during most part of the day both the transformers are under loaded.
7) Each transformer operates at a power factor of 0.9 lag and above.
8) The transformer efficiency calculated from its output and the losses is above 99.5 % and is almost same irrespective of the transformer loading. But the overall station efficiency considering the actual station power output and input in MVA varies directly with the percentage loading. The same is in the range of 60 to 93%. Ideally the values of transformer efficiency should have been matching with that of the station efficiency.
9) Presently there is no metering in place for recording transformer power factor, tertiary transformer performance and bus reactor performance. The presence of these metering would have certainly enhanced the analysis.

V. Conclusion and Suggestions

Based on the above observations and detailed analysis of the station performance, the following conclusions were drawn and accordingly suitable suggestions were proposed for energy conservation as well as for improvement in the station operational efficiency [8]:

1) The derived condition for maximum efficiency of the transformers is to operate them at 60.82% loading and above but presently these transformers are being loaded between 19 to 60%. The loading is near to 60% for very less duration of operation and it is generally well below this value for the major duration of any given day. It is a usual practice to design transformers to yield higher efficiencies at higher percentage loading [4], [10]. Hence it is suggested that

i)When station loading is in the range of 30 to 45%, only one transformer should be operated, since under this condition it would get loaded to between 60 to 90% where it would yield maximum efficiency.

ii) When station loading is below 30 %, only one transformer should be operated since this operation would improve the efficiency of the operating transformer and would also save the power loss that would have occurred in the second transformer.

iii) When station loading is above 45 % (i.e. one transformer would get loaded above 90 %), the second transformer must be brought into operation in parallel with the first transformer. This is to prevent the overloading of the single transformer.

2) Due to the adoption of the above suggestions (as given at serial No. 1 (i to ii), there may be chances of decrease in the Insulation Resistance (IR) value of the transformer which is kept in OFF condition. This may mainly be due to the high humidity and heavy rainfall in the coastal region of Goa. This limitation can be overcome by switching OFF one of the two transformers in a phased manner and alternatively.

3) An alternative to the above suggestion (as given at serial No. 2), would be to open the outgoing 220 kV side circuit breaker of one transformer while keeping its primary side connected to the 400 kV supply (instead of switching it OFF). By doing this only the load on this transformer could be transferred on to the second transformer which is also in operation. The no load losses of 101.4 kW suffered due to this measure could very well be compensated even if the efficiency of the loaded transformer improves by even small percentage.

Secondly due to this, the changeover time required for shifting the load from the loaded transformer on to the idle transformer in case of emergency due to the tripping of the loaded transformer would be extremely small. Thus this will improve efficiency by not affecting the system reliability to a larger extent.

4) For the purpose of controlling incoming voltage due to the Ferranti effect and light loading of the lines (on account of less power drawn by the State of Goa through this station), the bus and line reactors are being switched ON and also one 400 kV incoming line is being tripped. However, this solution makes the station operation tedious and causes an additional loss of power in the reactors, thus affecting the system efficiency, economics and reliability. To overcome this drawback, it is suggested to request the State of Goa for drawing its total power requirements (which is about 450 to 500 MW) through this station, thus loading and utilizing the station to its full capacity [1], [9].

5) The reasons for the mismatch between transformer efficiency and the station efficiency are presently difficult to be ascertained due to no metering for recording performance of the bus reactor. Hence it is assumed that the station efficiency is getting hampered due to loss of power in some of the station equipments other than the 315MVA transformers and more so in the 50MVAr shunt bus rector (which is the only equipment where such large amount of power may be absorbed). Thus the use of the bus reactor should be curtailed as much as possible [3].

6) The power loss and the corresponding reduction of station efficiency due to continuous switching ON of a conventional shunt reactor may be minimized by replacing it with a suitable Thyristor Controlled Reactors (TCRs). The TCRs may be connected in parallel and conjunction with harmonic filters through a Static VAr [5], [6] Compensating (SVC) step down transformer as shown in the Fig. 3.

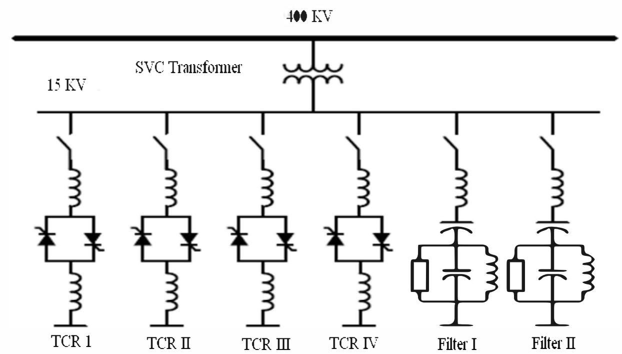

Fig. 3. Connection of TCRs, SVC and Filters.

These TCRs could be switched ON and OFF as per the variation in the station voltage. This would control the value of reactor remaining connected in the circuit, thus reducing the power loss in the reactor and hence improving the system efficiency and reliability compared to the present method.

7) It is learnt that the overcapacity of this station in the present scenario is due to the reason that at the time of assessing the station capacity in the year 1998, the power requirement of the state of Goa was projected to grow to 750 MW + 20 % by the end of 11th Five Year Plan. Unfortunately the projection of station capacity could not be realized till date for various reasons. This has forced the station to operate well below 60% of its capacity for most of the period in the last 8 years (since its commissioning in the year 2002). Hence, it is suggested to once again immediately study and reassess the present and future power requirement of the state of Goa and the station capacity may be trimmed and tailored suitably. Also the operational strategy for this station should be decided as well as planned foresightedly [7].

8) Presently this station is supplying power to the State of Goa only. An alternative suggestion to increase the optimum utilization of the station capacity could be to consider the feasibility of diverting its remaining and additional capacity to fulfill power requirements of the neighboring states and consumers [12].

9) Since there is no metering for recording transformer power factor, tertiary transformer performance and bus reactor performance, it is suggested that the above metering system should be put in place immediately.

VI. References

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TABLE 1
SAMPLE DATA SHEET OF EHV LINES (ON HOURLY BASES) FOR A DAY

TIME	400KV LINE I (I/P)		400KV LINE II (I/P)		400 KV BUS		220 KV BUS		220KV LINE I (O/P)		220KV LINE II (O/P)		220KV LINE III (O/P)		220KV LINE IV (O/P)		TOTAL STATION INPUT			TOTAL STATION OUTPUT		
HRS	MW	MVAR	MW	MVAR	KV	HZ	KV	HZ	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR	MW	MVAR	MVA	MW	MVAR	MVA
1	180	-104	0	0	409	49.70	224	49.70	48	19	47	18	38	3	38	6	180	-104	207.88	171	46	177.07
2	178	-104	0	0	409	49.84	225	49.84	48	19	47	18	38	3	38	4	178	-104	206.15	171	44	176.57
3	178	-102	0	0	411	49.93	225	49.93	51	21	50	19	35	0	35	3	178	-102	205.15	171	43	176.32
4	160	-94	0	0	413	49.60	226	49.60	44	19	43	18	33	-1	32	1	160	-94	185.56	152	37	156.43
5	170	-97	0	0	412	49.60	226	49.60	46	19	45	18	35	0	35	2	170	-97	195.72	161	39	165.65
6	173	-99	0	0	409	49.62	225	49.62	48	20	47	18	37	0	38	2	173	-99	199.32	170	40	174.64
7	183	-99	0	0	409	49.82	224	49.82	50	19	49	18	39	1	41	3	183	-99	208.06	179	41	183.63
8	176	-99	0	0	409	49.90	225	49.90	48	20	47	19	38	0	38	1	176	-99	201.93	171	40	175.61
9	185	-107	0	0	400	49.84	220	49.84	50	22	49	21	41	3	41	5	185	-107	213.71	181	51	188.04
10	200	-127	0	0	396	49.56	218	49.56	57	31	57	29	41	6	41	7	200	-127	236.91	196	73	209.15
11	205	-133	0	0	390	49.46	222	49.46	59	32	59	30	43	6	43	8	205	-133	244.36	204	76	217.69
12	107	-75	105	-73	417	49.64	227	49.64	61	35	59	33	42	9	42	10	212	-148	258.54	204	87	221.77
13	109	-72	107	-70	415	49.70	226	49.70	59	31	59	29	44	8	45	10	216	-142	258.49	207	78	221.20
14	105	-68	105	-68	410	49.39	225	49.39	59	32	59	32	42	6	40	7	210	-136	250.19	200	77	214.31
15	112	-73	112	-73	411	49.73	224	49.73	58	32	58	32	49	12	50	12	224	-146	267.37	215	88	232.31
16	109	-70	109	-70	412	49.90	225	49.90	57	31	57	31	47	9	47	11	218	-140	259.08	208	82	223.57
17	105	-68	105	-68	410	49.72	224	49.72	58	31	58	31	43	9	43	9	210	-136	250.19	202	80	217.26
18	100	-70	100	-70	415	49.88	227	49.88	58	31	58	31	40	7	40	9	200	-140	244.13	196	78	210.95
19	100	-68	100	-68	415	49.69	226	49.69	56	30	56	30	40	8	40	9	200	-136	241.85	192	77	206.86
20	104	-70	104	-70	417	49.53	227	49.53	62	29	62	29	30	10	37	12	208	-140	250.72	191	80	207.07
21	94	-65	92	-63	419	49.40	228	49.40	58	24	57	23	31	9	31	10	186	-128	225.78	177	66	188.90
22	94	-58	92	-58	418	49.67	228	49.67	56	22	56	21	33	6	33	7	186	-116	219.20	178	56	186.60
23	97	-53	95	-53	420	49.66	229	49.66	55	19	54	18	38	4	38	6	192	-106	219.31	185	47	190.87
24	0	0	175	-97	411	50.11	226	50.11	52	21	52	20	34	-3	34	0	175	-97	200.08	172	38	176.14

TABLE 2
SAMPLE DATA SHEET OF EHV TRANSFORMERS AND BUS REACTOR (ON 4 HOURLY BASES) FOR A DAY

TIME	TRANSFORMER I						TRANSFORMER II						
	HV CURRENT			HV POWER		TAP POS.	HV CURRENT (IN AMPS)			HV POWER		TAP POS.	BUS REACTOR MVAR
HRS	R	Y	B	MW	MVAR		R	Y	B	MW	MVAR		
04:00	160	160	160	81	28	10	160	160	160	81	28	10	49
08:00	170	170	170	90	29	10	170	170	170	90	29	10	49
12:00	180	180	180	108	54	10	180	180	180	108	54	10	49
16:00	160	160	160	110	50	10	160	160	160	110	50	10	49
20:00	160	160	160	104	50	10	160	160	160	104	50	10	50
24:00	140	140	140	90	29	10	140	140	140	90	29	10	50

TABLE 3
Data Sheet of Performance Analysis of the EHV Transformer

P.F (LAG) (OUTPUT MW/ MVA)	% LOADING (OUTPUT MVA/630)	% STATION EFFICIENCY (OP MVA/ IP MVA)	TRANSFORMER KVA RATING	NO LOAD LOSS (KW)	LOAD LOSS (KW)	% TRANSFORMER EFFICIENCY	DIFF. OF % EFFICIENCY
0.899323	19.23846194	60.86343298	315000	101.4	10.14494583	99.9981326	39.13469961
0.958875	20.69222811	67.44055339	315000	101.4	11.73609322	99.99836959	32.5578162
0.959247	21.34610823	69.67900614	315000	101.4	12.48954019	99.99841911	30.31941297
0.96645892	23.486164	75.4509891	315000	101.4	15.11935324	99.99857017	24.54758107
0.926258	24.84824183	80.35928177	315000	101.4	16.9238967	99.99858699	19.63930522
0.91884	26.94909023	81.30113227	315000	101.4	19.90660746	99.99868148	18.69754921
0.94045331	28.01755919	81.90682024	315000	101.4	21.51640111	99.99875798	18.09193774
0.94288605	28.11361609	82.82499287	315000	101.4	21.66418997	99.99876514	17.17377227
0.97618706	29.2683951	83.12645377	315000	101.4	23.48047367	99.998851	16.87239723
0.93698	29.98487903	83.66483039	315000	101.4	24.64413832	99.99882921	16.33399882
0.9449233	30.06878819	84.37614236	315000	101.4	24.78225876	99.99884202	15.62269966
0.97735788	31.50703689	85.99357473	315000	101.4	27.20972537	99.9989268	14.00535207
0.96808527	32.30070979	86.16074935	315000	101.4	28.59783573	99.99894028	13.83819093
0.93763837	34.7038727	86.98943101	315000	101.4	33.01147417	99.99897195	13.00954094
0.93157762	34.92965252	87.36816767	315000	101.4	33.44240993	99.99897094	12.63080327
0.92412505	35.72662926	87.96127639	315000	101.4	34.98590577	99.99898207	12.03770568
0.94323534	35.84420813	87.37376716	315000	101.4	35.21656689	99.99900541	12.62523825
0.93117796	36.137876	88.02440492	315000	101.4	35.79598211	99.9989993	11.97459438
0.95326054	37.29888541	88.07039769	315000	101.4	38.13297984	99.99904729	11.9286496
0.91892786	37.82876378	88.52004431	315000	101.4	39.22413127	99.99902272	11.47897841
0.96637248	38.27108884	88.67316364	315000	101.4	40.14677576	99.99907915	11.32591551
0.95726389	38.96688001	89.94106945	315000	101.4	41.61983018	99.99908325	10.0580138
0.95334223	39.95966724	89.56037121	315000	101.4	43.76760292	99.99909677	10.43872555
0.95364172	40.61290326	89.60011777	315000	101.4	45.21027085	99.99910774	10.39898997
0.94752145	41.21027447	89.24763484	315000	101.4	46.55003905	99.99911135	10.7514765
0.94752145	42.51865152	89.64045025	315000	101.4	49.55277727	99.99913039	10.35868015
0.9367778	43.54677361	89.97083727	315000	101.4	51.97817208	99.9991342	10.02829692
0.96377223	44.63282074	89.82181908	315000	101.4	54.60315092	99.99917139	10.17735231
0.93647324	45.25591406	88.94786787	315000	101.4	56.13835954	99.99915433	11.05128646
0.94998996	48.28789534	89.66681251	315000	101.4	63.91246813	99.99919514	10.33238263
0.9671548	51.20567019	92.19278694	315000	101.4	71.86958629	99.99922921	7.806442267
0.93177739	52.46842144	90.74500391	315000	101.4	75.45795515	99.99920667	9.254202769
0.9486833	55.21437184	91.89381024	315000	101.4	83.56286218	99.99923107	8.105420827
0.94811911	56.41913836	91.07635497	315000	101.4	87.24929655	99.9992334	8.922878434
0.95033737	57.12257136	92.66566144	315000	101.4	89.43850542	99.99923636	7.333574914