International Journal for Research in Engineering Application & Management (IJREAM)
ISSN : 2454-9150 Vol-05, Issue-04, July 2019

Exploration and exploitation of solar absorption chillers in air-conditioning system and its impact on electrical distribution feeders

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Abstract: This paper deals with the Techno-economic analysis of solar absorption chillers and conventional Electrical Chillers. Absorption technology is one of the oldest methods of space cooling mechanically. The refrigerant used is actually water, as that is the working medium that experiences a phase change and causes the cooling affect. The other fluid that drives the process is a salt, generally lithium bromide (LiBr). Heat is used to separate the two fluids; when they are mixed in a near vacuum environment. Solar absorption chillers use only small fraction of electricity as compared to the conventional vapour compression chillers. Vapour absorption systems work with non-CFC environmentally friendly refrigerants such as water or ammonia. Solar thermal heating (enhanced) used to get the operating temperature of Li-Br absorption systems at 90°C. The capital cost of the solar absorption system is higher as compared to Conventional Chiller systems, but when viewed in totality of reduced electrical service size, transformer, switchgear and cables, the solar absorption becomes comparable to conventional (electrically operated) compression systems. And also analysed its impact on electrical energy consumption, cost optimisation and reduction in size of the electrical distribution feeders.

Keywords: Coefficient of Performance, Automatic Power Factor Correction, Vapour absorption, Energy conservation, solar thermal water heater, Diversity factor.

I. INTRODUCTION

Vapor absorption refrigeration systems using water-lithium bromide pair are extensively used in large capacity air conditioning systems, they enjoy cooling capacities ranging from kilowatts to megawatts which match with small residential to large scale commercial or even industrial cooling needs.

LiBr absorption chillers can operate with low regenerating temperature ‘80°C to 110°C’, offering the possibility to work with flat plate collectors which are effective and less expensive. Lithium bromide aqueous solution is one of many other solutions widely used in the operation of the absorption heat pumps that are used for cooling purposes. It has been used since the 1950 when the technologies were pioneered by several manufactures in the US. In these systems water is used as refrigerant and a solution of lithium bromide in water is used as absorbent. Several investigations have been conducted: Txilingiris, presented a microcomputer model to design solar (LiBr-H_2O) absorption cooling system in Greece using about 25 years’ statistical treatments of meteorological data Ghaddar et al., modeled and simulated a solar absorption system in Beirut, the cooling power at the evaporator was modeled as a variable load. The results showed that for each ton of refrigeration a minimum area of 23.3 m^2 of flat plat collector is required. The impact of the enhanced solar water heating system in air- conditioning system specifically the solar absorption chillers widely used in industries (IT, Process and R&D laboratories where the precision air-conditioning is required) to reduce the running cost and installation cost of the electrical equipment installed at the consumer side.

Due to the increasing energy consumption of air-conditioning in building and the need to reduce Co_2 emissions to the environment, the interest of using renewable energy sources shows up stronger than ever. Solar energy, often correlated to the cooling demand of a building [1], is probably one of the best energy resources for air conditioning systems. The major part of the solar cooling systems use thermally driven single effect absorption chiller [2], which are available on the market in a wide range of capacities and designed for different applications. But only few chillers are available with a cooling capacity lower than optimized design for solar applications [3]. For small scale applications, like single family house, there are only few available chillers (less than 10 kW). Therefore the development of low power

 DOI : 10.35291/2454-9150.2019.0298

ISSN : 2454-9150 Vol-05, Issue-04, July 2019

cooling and air conditioning systems is of particular interest [4]. There are two main working pairs for absorption chillers: water-lithium bromide and ammonia-water. Ammonia-water chillers are particularly interesting because of their low production and maintenance cost [5]. Moreover the high pressure thermodynamic cycle is favorable for internal heat and mass transfer optimization, reduction of the ammonia-water solution quantity, lower hydraulic pressure drops and a compact final design. Since cooling and heating systems of buildings cause between 30 and 50% of the global energy consumption, increased efficiency of such systems considerably reduces energy consumption [6]. The vapour-absorption cycle is considered to be the best in terms of energy performance today. In addition, it has the potential to be improved among the several heat-powered cycles [7].

The essential condition in absorption chillers is the availability of an inexpensive or even free heat source such as waste heat. Several studies have been made using solar energy [8] [9]. Water, as a refrigerant and lithium-bromide as an absorbent, is one of the most used working fluid pairs in current absorption chillers [10]. One of the earliest dynamic simulations of absorption refrigeration systems has been performed by Jeong et al. [11] for a steam driven heat pump. The model assumes that solution mass storage in the vessels, thermal capacity heat storage, and flow rates (vapour and solution) are calculated according to the pressure differences between vessels. Later, Fu et al. [12] developed a library of elemental dynamic models for absorption refrigeration systems, in which the components are described as lumped processes involving two-phase equilibriums. In a series of two papers, Kohlenbach and Ziegler [13] [14] presented a simulation model and its experimental verification for a single-effect water/LiBr chiller. As a special feature, all of the thermal capacities have been divided into an external part (influenced by the temperature of the external heat carriers) and an internal part (influenced by the temperature of the refrigerant or the absorbent). Moreover, a transport delay time has been assumed in the solution cycle. Matsushima et al. [15] developed a program using object-oriented formulation and parallel processing to simulate the transient operation of a triple-effect absorption chiller. A special algorithm based on the pressure difference and flow resistance between the generators and the absorber has been used to calculate the flow rate of solution. Wu et al. [16] experimentally studied the equilibrium pressure, equilibrium temperature, and gas composition of NH_3-H_2O-LiBr ternary mixture for its application in industrial absorption chillers and heat pumps. Xie et al. [17] investigated the relationship of coefficient of performance (COP) of a lithium-bromide absorption chiller with solution concentration of LiBr/H_2O. Papaefthimiou et al. [18] developed a mathematical model for analysing the heat and mass transfer process of LiBr-H_2O absorption on a horizontal tube, and a good agreement with the test data was obtained.de Lucaset al. [19] added formats and lithium-nitrates in the lithium bromide solution and analysed the effect of generation temperature, condensing temperature, and evaporation temperature on system performance. This action was found to increase the COP by 30% and the solution circulation rate to decrease by 12%.

In recent years, finding ways to improve absorption-system efficiency has been a great challenge for researchers [20] [21]. Works have mainly focused on inventing new or hybrid cycles, finding new working fluids, and improving the heat and mass transfers of the absorption refrigerator. The performance of absorption cycles is attributed to the thermodynamic properties of the working pairs which consist of the refrigerant and the absorbent. Most commonly used working pairs are ammonia + water solution (NH_3 + H_2O) and aqueous solution of lithium bromide (H_2O + LiBr). However, Zhang and Hu [22] have identified corrosion, crystallization, and toxicity as inevitable weaknesses of these working pairs. The need for working pairs not susceptible to these weaknesses has become the focus of research. Best et al., suggested that the main technical problem of cooling systems that are powered by solar energy is that the system is so dependent upon the environment factors such as the temperature of the ambient air and solar radiation, Schweigler et al., further disclosed an absorption chiller machine in which plate type heat exchangers are used in the absorber and condenser, [23]. Balghouthi et al., accomplished a simulation using TRNSYS program to size the different components of solar absorption.

II. VAPOUR ABSORPTION CHILLER SYSTEMS

Vapor absorption systems work with non-CFC refrigerants such as water or ammonia. Refrigerant of Li Br Absorption Machine is pure (distilled) water. The refrigerant water flows in a closed loop and is re-circulated. These systems find acceptability in the commercial air-conditioning or process cooling. Absorbent is a material that has great affinity with water. It is well known that when salt (such as Na Cl) is left in a high-humidity atmosphere, it becomes sticky. Waste heat from the exhaust of a gas turbine, or from water jackets of a reciprocating engine is recovered for use through heat exchangers. The heat from the flue gases of furnaces, dryers, kilns and boilers can be utilized to drive the hot water or steam run chillers. In the case of dual effect absorption chillers, high-pressure steam or direct firing from natural gas or oil, is the energy source.

Li-Br is a non-toxic aqueous solution but very corrosive in oxygen. Absorbent in the ammonia based absorption machine is water. Cooling water is required to cool the absorbent and the refrigerant vapor. The cooling water flows through the Absorber and the Condenser items of the

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VAM. The heat gain in the cooling water is rejected in a cooling tower and thus is an open loop. Around 2% of water is lost as a result of evaporation, drift and blow down in the cooling tower that needs make-up. The working fluid is a mixture of a refrigerant and absorbent. The schematic diagram of the system is shown in Figure 1. Heat (e.g., solar input) is transferred to vaporize the refrigerant from the solution entering the generator. The vaporized working fluid is then passed through a condenser, exiting as a liquid. Heat is rejected at an intermediate temperature from the condensing process to a heat rejection water stream. The fluid then expands through a throttling valve to lower the pressure, and enters an evaporator, where it removes heat from an incoming stream to produce chilled water. This produces the useful cooling effect, as the chilled water is used for space-cooling in the distribution portion of the air conditioning system.

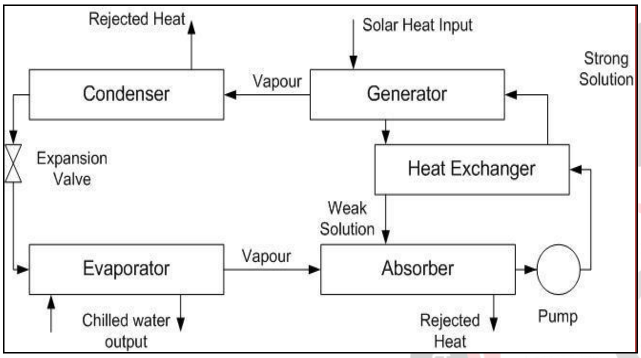

Fig.1 Schematic of a single-effect solar absorption chiller

2.1 PROCESS FLOW OF VAPOR ABSORPTION SYSTEM

The water boils at 100°C in the atmospheric pressure and when the pressure is higher than the atmospheric pressure, water boils at a temperature higher than 100°C while when the pressure is lower (vacuum), water boils at a temperature lower than 100°C and also water boils at 89°C at the summit of 2750 m mountains. The water is heated up in the solar flat plat collector and fed to the solar hot water tank. The heated water is circulated through by-pass value and circulating pump until the hot water temperature reaches to 90°C by using PLC logic. Once the temperature reached 90°C the solenoid value opens and the hot water flows in the heat exchanger to heat up the LiBr. The secondary system comprising of condenser, chilled water, cooling towers are common for both the conventional absorption and solar absorption chillers. The process controlled flow diagram as shown in the figure 2, its ladder logic as shown in figure 3 and the PLC Control I/Os are as shown in the Table1.

Table 1. PLC Control I/O Table

Inputs	Description	Outputs	Description	Timer	Description	Timer Value
B01	Start	B20	Command to VAC	T02	Solar Pump start	2.0 min
B02	Pressure Interlock	B21	Spare	T04	Hot Water timer	3.0 min
B03	Spare	B22	Sol. Valve ON			
B04	Hot water Inlet Temp High	B23	Solar water Pump ON			
B05	Trouble	B24	Hooter			
B06	Chiller trouble	B26	Cooling water Pump ON			

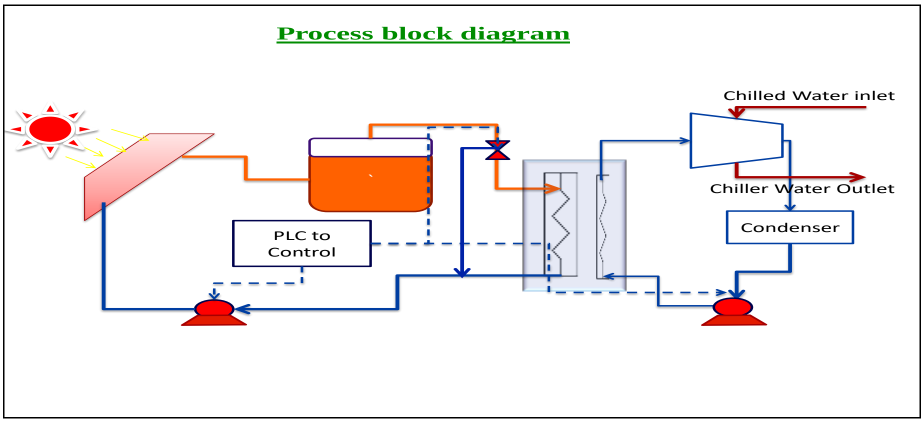

Fig.2. Process controlled flow diagram.

DOI : 10.35291/2454-9150.2019.0298

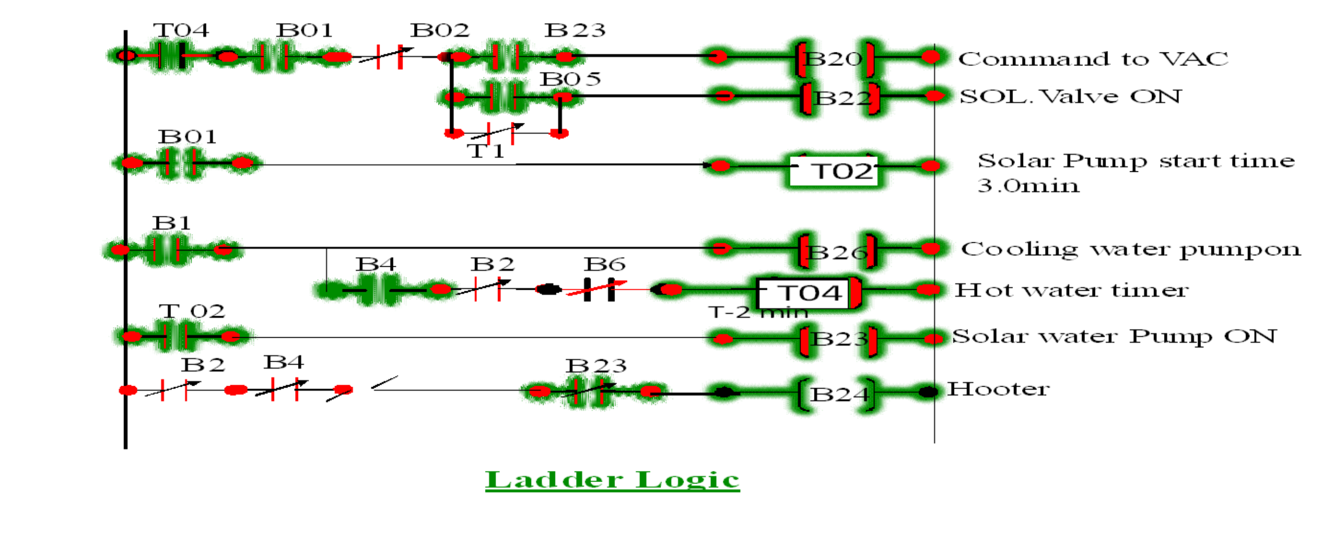

Fig.3. PLC ladder logic of Solar Absorption chiller

2.2 EXPERIMENTAL DATA OF WATER FLOW IN A FLAT PLATE COLLECTOR

Experiments conducted on Solar thermal systems for enhancing the temperature by using different technics and it was investigated that, the maximum temperature 90°C will get with Nano fluid (Al_2O_3-17.91 gms) at 0.03% volume concentration with twisted inserts of aspect ratio = 2. The outlet fluid is collected at the heat exchanger, which is tightly insulated and the inlet and outlet flows are controlled by PLC (Programmable Logic Controller) with I/O's (Input and Output devices) i.e., inlet and outlet solenoid valves and fluid circulating pumps. If the temperature is less than 90°C, the outlet solenoid valve is continuously closed and it opens till the temperature reaches 90°C.

Experiments are conducted from 11:00 hrs to 15:00 hrs with the 30 minutes interval. The inlet, outlet atmospheric temperatures are noted and the collector output and efficiencies with mass flow rate (m= 0.05 kg/sec) with water without inserts are summarized in table 2. The corresponding graph is shown in figure 4.

Table 2. Temperature distribution in a flat plate collector with water (mass flow rate = 0.05 kg/sec) without insert.

ime (Hrs)	Inlet Temp.°C (T_i)	Atm. Temp.°C (T_a)	Outlet Temp.°C (T_o)	Collector Temp. °C, $Tc = (T_o+T_i)/2$	$(T_c - T_a)$ Temp. °C	$(T_c-T_a)/G_T$	Collector output, (Q) w/m²	Collector efficiency (η_i)
11:00	32.50	34.60	38.00	35.25	0.65	0.0009	1151.23	0.7972
11:30	37.90	35.70	44.00	40.95	5.25	0.0073	1276.65	0.8840
12:00	43.10	36.20	49.20	46.15	9.95	0.0138	1276.67	0.8840
12:30	48.30	38.70	54.60	51.45	12.75	0.0177	1318.65	0.9130
13:00	54.30	40.80	60.70	57.50	16.70	0.0231	1339.46	0.9278
13:30	54.20	40.90	59.80	57.00	16.10	0.0223	1172.09	0.8117
14:00	42.10	40.60	47.30	44.70	4.10	0.0057	1088.43	0.7537
14:30	41.10	40.10	45.90	43.50	3.40	0.0047	1004.54	0.6957
15:00	38.20	40.00	42.40	40.30	0.30	0.0004	879.12	0.6089

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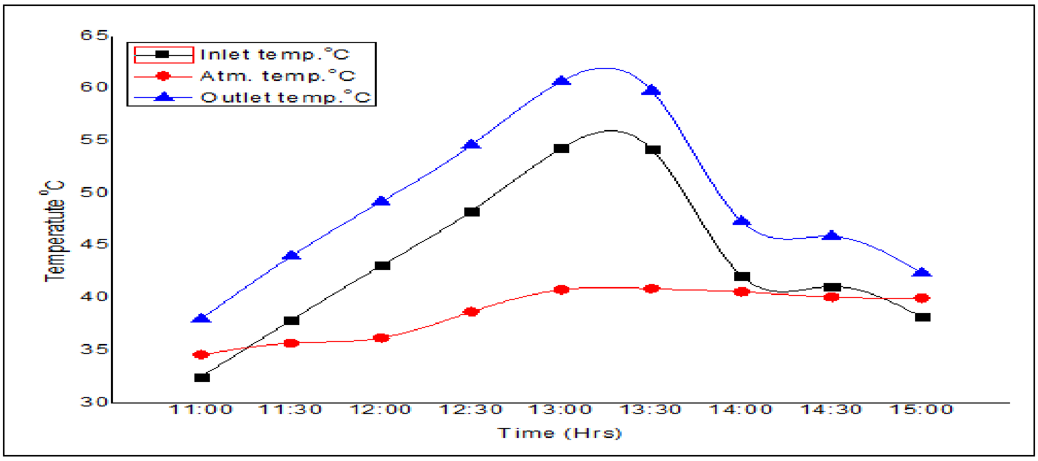

Fig. 4. Temperature distribution in a flat plate collector with water (mass flow rate = 0.05 kg/sec) without insert.

Experiments are conducted from 11:00 hrs to 15:00 hrs with the 30 minutes interval. The inlet, outlet atmospheric temperatures are noted and the collector output and efficiencies with mass flow rate (m= 0.05 kg/sec) Nanofluid (Al_2O_3-17.91 gms) with twisted insert, AR=2 are summarized in table 3. The corresponding graph is shown in figure 5.

Table 3. Temperature distribution in a flat plate collector with (mass flow rate = 0.05 kg/sec) Nanofluid (Al_2O_3-17.91 gms) with twisted insert, AR=2.

Time (Hrs)	Inlet Temp.°C (T_i)	Atm. Temp.°C (T_a)	Outlet Temp.°C (T_o)	Collector Temp. °C, Tc =(T_o+T_i)/2	(T_c – T_a) Temp. °C	(T_c-T_a)/G_T	Collector output (Q) w/m^2	Collector efficiency (η_i)
11:00	45.20	40.80	52.00	48.60	7.80	0.0108	1423.16	0.9856
11:30	52.00	41.40	58.80	55.40	14.00	0.0194	1423.17	0.9855
12:00	58.80	42.10	65.60	62.20	20.10	0.0278	1423.15	0.9858
12:30	65.30	42.20	72.10	68.70	26.50	0.0367	1423.23	0.9856
13:00	72.00	44.60	78.80	75.40	30.80	0.0427	1423.24	0.9853
13:30	78.70	46.10	85.50	82.10	36.00	0.0499	1423.17	0.9853
14:00	85.40	46.60	92.20	88.80	42.20	0.0584	1423.17	0.9860
14:30	83.00	45.50	89.50	86.25	40.75	0.0564	1360.47	0.9425
15:00	72.30	44.80	78.60	75.45	30.65	0.0425	1318.59	0.9128

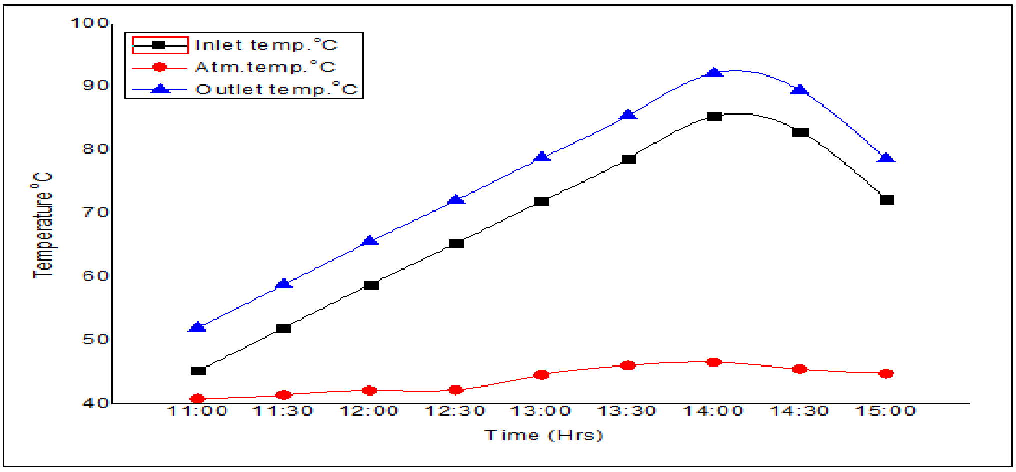

Fig.5. Temperature distribution in a flat plate collector with (mass flow rate = 0.05 kg/sec) Nanofluid (Al_2O_3-17.91 gms) with twisted insert, AR=2.

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The flow chart for the solar absorption chiller and its controls and safety systems are as shown in the figures 6,7 &8.

2.3 SOLAR ABSORPTION COOLING

Solar absorption cooling (SAC) utilizes harmless working fluids (refrigerants) such as water to produce chilled fluid for the removal of heat through space-cooling (Balghouthi et al., 2005). The thermal coefficient of performance (COP) of an absorption cooling system varies with operating conditions, including change in temperature levels and load.

III. CASE STUDY

The study has been conducted for HVAC systems with Conventional Chillers and with Solar Absorption Chillers and its effect on Electrical Distribution feeder network. The designed capaicties of the HVAC systems of facility is 150 TR (2 nor of 75 TR) and 1 Nor of 75 TR as a stand-by for the both chillers. The required desigbed temperature is 22^{o}C +/- 2^{o}C. As per the load details, a 500 kVA Transformer is conneced to cater the loads of the facility which is connected through the cables, LTDB's (low tension distribution boards) and Capacitor panal.

In LTDB, each feeder is connected to the main equipment and anciliary equipments. The capacitor panal is decided based on the resistive loads with considering the fixed compensation and variable compensation. By using the SAC (LiBr-Water), the capacities of the Electrical Power Systems is re-designed by replacing the conventional (Electrical) heaters with enhanced Solar Water Heating System for the desired capacity. Electrical Compressors are replaced with SAC sysgtem. The total system is optimised in terms of capacities of the equipments, Electrical Energy consumption and price.

The feeder wise details of the both the systems are as shown in the schematic diagrams of the conventional and absorption systems are shown in figure 9 & 10. The Load details of Equipment's with the Conventional Electrical Chiller Approach (CEC) and SAC are tabulated in table 6. The desired Capacitor panel with the CEC Approach and SAC are tabulated in table 7. The cost analysis of both the systems is discussed in table 8.

a) Comparison of Electrical Power consumption for Conventional Electrical Chillers and Solar Absorption Chillers:

The cost of electrical power consumption of the Conventional Electrical Chillers (by considering 75 TR Chillers) is Rs 5, 04,000 per month by considering 70 kW per 10 Hrs per day for two systems (1400 units @ Rs 12 per unit under HT-II category tariff for 30 days). The overall savings is Rs 5, 04,000 per month. Annually savings is Rs 60, 48,000/-.Where as in case of Solar absorption system, the cost of electrical power consumption is Rs 14,400 per month by considering 2 kW motor running 10 hrs per day for two systems (40 units @ Rs 12 per unit under HT-II category tariff for 30 days). For SAC system, the overall savings annually is Rs 1, 72,800/-.

b) Load comparison of Electrical installations of Conventional Electrical Chillers and Solar absorption Chillers:

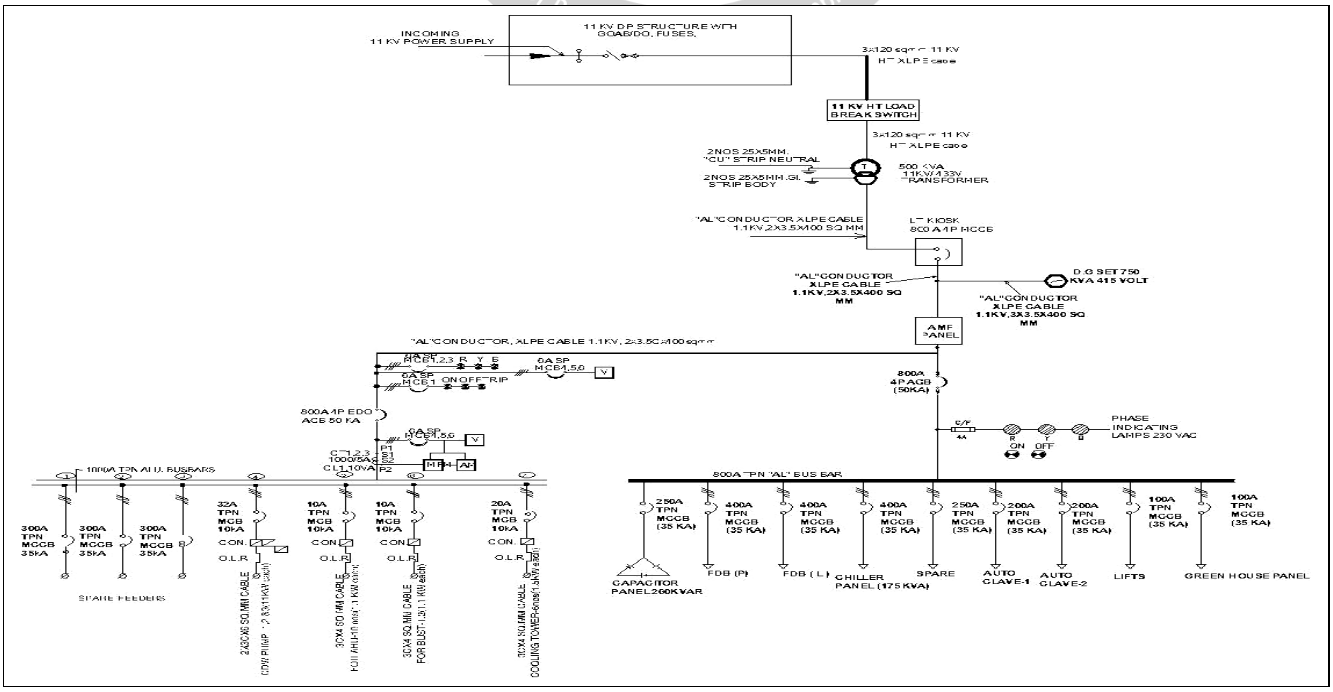

Fig 6. Single Line Diagram (SLD) of the CEC Approach

Table 4. Load details of Equipment's with CEC Approach

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	Description	Ø	Load (kW)	CEC Approach		SAC approach	
				UoM	Total Load (kW)	UoM	Total Load (kW)
1	75 TR Chiller	3	72.20	03 Nos	210.60	01 Nor	70.20
2	Auto clave equipment	3	72	03 Nos	144.00	01 Nor	72.00
3	Miscellaneous Loads	3		LS	251.55	LS	251.55
Total connected load in kW					606.15		393.75
Total load in kW by considering diversity factor 0.7					424.305		275.625

(Note: Miscellaneous Loads includes primary pumps, secondary pumps, chilled water pumps, cooling tower pumps, booster pumps, AHU's, FCU's, EF's, Lifts, fans and other raw power loads).

Total connected load for CEC is 606.15 kW, by considering the diversity factor as 0.7; the connected load is 424.305 kVA. Hence proposed size of the ttransformer is 500 kVA for CEC approach. In case of SAC approach, the total connected load is 393.75 kVA, by considering the diversity factor as 0.7; the connected load is 275.625 kVA. Hence proposed size of the transformer is 280 kVA.

c) Comparison of Power Factor (PF) for electrical conventional chiller CEC and SAC:

The existing P.F of eelectrical power system is 0.8, desired PF is 0.98. To improve the P.F from 0.8 to 0.98, need to increase the size of APFC capacitors.

Table 5. Desired Capacitor panel with CEC and SAC

S. No	Description	kVAR for CEC	**Description**	kVAR for SAC
1	Apparent power (maximum demand of load (kVA)	400	Apparent power (maximum demand of load in kVA)	250
2	Present power factor	0.8	Present power factor	0.8
3	Desired power factor	0.98	Desired power factor	0.98
4	Transformer capacity (kVA)	500	Transformer capacity in kVA	280
5	Transformer no load losses in %	6%	Transformer no load losses in %	5%
6	kVAR for present power factor i.e $(400*\sqrt{(1-(0.8*0.8))})$ =kVAr-P	240	kVAR for present power factor i.e $(250*\sqrt{(1-(0.8*0.8))})$	150
7	kVAR for desired power factor i.e $(400*\sqrt{(1-(0.98*0.98))})$ =kVAr-D	80	kVAR for desired power factor i.e $(250*\sqrt{(1-(0.98*0.98))})$	50
8	Required kVAr based on power factor (KVAr - P) - (KVAr - D)	160	Required kVAr based on power factor (KVAr - P) - (KVAr - D)	100
9	Transformer losses@ 6% of 500 kVA	30	Transformer losses @ 5% of 280 kVA	14
10	20% extra for auto switching of capacitors	38	20% extra for auto switching of capacitors	23
	Total required kVAR for APFC Panel	228	Total required kVAR for APFC Panel	137

Required capacitance for cconventional chiller is 228 kVAR (available size 260 kVAR) by considering the fixed compensation of 500 kVA Transformer is 6% and where as in case of Solar Absorption Chiller, the required capacitance is 137 kVAr (available size 150 kVAR) by considering the fixed compensation of 280 kVA Transformer is 5% as indicated in table 5 and the cost analysis of the CEC and SAC systems are indicated in the tables 6.

 DOI : 10.35291/2454-9150.2019.0298

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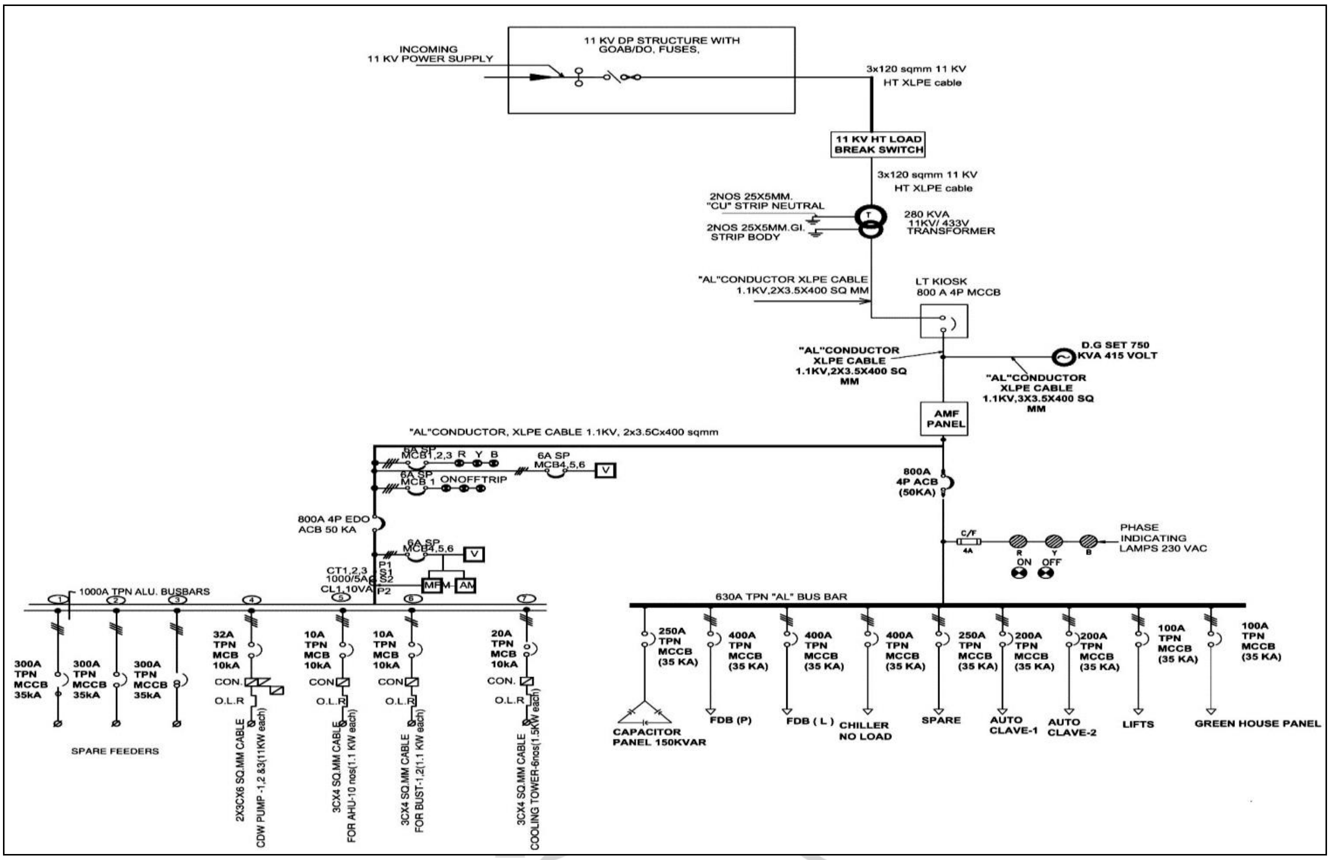

Fig 7. Single Line Diagram (SLD) of SAC approach

d) Installation cost analysis of the CEC system and SAC systems:

Table 6. Cost Analysis of CEC system and SAC.

S No.	Description	Qty	Unit	CEC		Qty	Unit	SAC	
				Rate (Rs)	Amount Rs)			Rate (Rs)	Amount (Rs)
1	3Cx120 Sqmm 11 KV XLPE insulated aluminum cable	56	Mtr	1,200	67,200	56	Mtr	1,200	67,200
2	3.5Cx185 Sqmm XLPE insulated aluminum cable	600	Mtr	900	5,40,000	300	Mtr	900	27,000
3	3.5Cx400 Sqmm XLPE insulated aluminum cable	1277	Mtr	1,814	23,16,989	800	Mtr	1,814	14,51,520
4	500 kVA distribution Transformer (oil filled)	01	each	7,20,277	7,20,277	01	each	4,32,166	4,32,166
5	800A 4P On-Load change over switch HT Breaker	01	each	79,218	79,218	01	each	63,374	63,374
6	Main LT Panel	01	Set	2,28,683	2,28,683	01	Set	1,14,319	1,14,319
7	Floor distribution panels (2 No) and Lift Panels (2 No)	01	Set	2,69,039	2,69,039	01	Set	2,69,039	2,69,039
8	750 kVA DG Set	01	Set	75,59,000	75,59,000	01	Set	41,57,450	41,57,450
9	AMF Panel (1200A)	01	Set	10,27,515	10,27,515	01	Set	6,67,884	6,67,884
10	LT kiosk at Sub Station Yard (800A)	01	Set	2,88,157	2,88,157	01	Set	2,30,525	2,30,525
11	APFC Panel (Thyristor Switched) (260 kVAR)	01	Set	4,59,400	4,59,400	01	Set	3,68,000	3,68,000
12	Main HVAC Panel	01	Set	7,85,000	7,85,000	01	Set	4,31,750	4,31,750
13	HVAC sub-Panels (2 Nos)	01	Set	50,000	1,00,000	01	Set	50,000	1,00,000
Total cost of the system Rs					1,44,40,478	Rs			83,80,227

(Note: costs are based on the market price excluding GST)

IV. CONCLUSION

Installation cost of Electrical Distribution System with Conventional (electrically operated) Absorption chillers is Rs 1.44 Crores; where as in the Solar Absorption Chiller Electrical Distribution System it is Rs 0.84. The overall reduction in the cost of installation is 42%. Annual savings by using the Solar Absorption Chillers is Rs 60 lakhs.

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Capacity of the distribution transformer in case of Conventional Electrical Chiller is 500 kVA whereas in case of Solar Absorption Chiller is 280 kVA. So, the reduction in the capacity of transformer is 44%. Capacity of the APFC panel in case of CEC is 228 kVAR whereas in case of SAC is 137 kVA. So, the reduction in the capacity of APFC panel is 40%. Through the investigation and cost analysis, It is concluded that the, overall efficiency of the SAC is most cost effective than CEC systems.

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 DOI : 10.35291/2454-9150.2019.0298