IOE Graduate Conference, 2020-Summer
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2020 Month: June Volume: 8
Peer Reviewed

Analysis on AC-DC Hybrid Power Supply System: A Case Study for Hospital Building in Kathmandu, Nepal

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Abstract

Because of some limitations found to use either completely DC supply system or completely AC supply system, hybrid AC-DC supply system become prone topic of the discussion for effective power supply solution as it helps to reduces multiple conversion losses that may occur from generation to end use point. Implementation of hybrid supply system within the hospital building can save the energy as maximum numbers of DC loads like Light Emitting Diode (LED) lights, fan and computer charging system are operated for maximum number of hours in comparison with other buildings. This research includes the development of hybrid supply system for a hospital building in which all lighting devices, fan and computer charging system were supplied from DC side and remaining loads being supplied from existing AC line. 48 volt DC line has been developed by converting existing AC supply. Required AC-DC and DC-DC converter with regulator is designed and simulated in PLECS (Piecewise Linear Electrical Circuit Simulation) software. Wire sizes required to develop DC wiring model is selected by maintaining 4 percent voltage drop limit from DC source point (AC to DC conversion point). Based on the simulation results losses in developed model is calculated and energy saving opportunity on implementing this model is evaluated. Certainty and sensitivity on energy saving with change in factors like hour of operation per day and percentage of load supplied by uninterruptible power supply (UPS) at a time is analyzed using crystal ball simulation.

Keywords

AC-DC hybrid supply model, Rectifier, Filter, Closed loop, Buck converter, Sensitivity analysis

1. Introduction

After 1950s, with progress in advanced power electronic devices (PEDs) technology and it's commercialization for power conversion (like: Rectifier, inverter and choppers), DC system recognizes some major advantage over AC system [1]. However, there are some limitations found to use as either completely DC supply system or completely AC supply system from generation to consumption point. If distributed photo-voltaic generators and battery energy storage system is to be connect to the AC power supply system, DC-DC and DC-AC conversion steps are required and to feed the DC loads from such supply system, AC-DC conversion is needed. Similarly if generation technologies of AC type (like: Hydro Generator, Diesel Generator etc.) is to be connect to the completely DC power grid only, AC-DC conversion steps is required and to feed the AC loads from such supply system DC-AC conversion is needed.Such multiple conversion steps will results the increase in loss [2]. Multiple conversion loss can be minimized by using hybrid AC-DC supply system. Hybridization of transmission and primary distribution depends on the service provider authority (NEA in Nepal). However for large buildings like Hospital, commercial Mall etc, Owner can develop hybrid supply structure with in the building. Hybrid AC-DC supply structure for building consists of an existing AC supply line which is coupled with a DC supply line using an AC to DC converter. AC loads are directly supplied from AC line and DC loads from DC line of hybrid AC-DC system.

Past studies and research suggested that implementation of hybrid AC-DC network would be effective and will provides better security, reliability and operation of the network and will improve the power consumption efficiency of buildings [3, 4, 5]. However, in past studies and research number and types of DC and AC loads are different. They considered DC loads such as DC refrigerators, DC air conditioners and DC air purifiers etc. In Nepal most of such loads are of AC type and it is costly to replace them all. Moreover heavy types of load which are quite far from DC source require larger size of wires in order to maintain allowable voltage drop within the limit whereas decrease in the amount of DC loads may make the integration of DC network in an existing AC network inefficient. So, this study focuses on the Energy saving opportunity when implementing hybrid AC-DC supply network in a building only by replacing AC lighting, fan and computer charging system by DC system as cost of replacement of such fixture are comparatively less than the cost of replacement of other devices like, refrigerators, air conditioners, air purifiers etc. Since in hospital building lighting loads are operated for maximum time so more energy can be save by replacing efficient DC lighting system in comparison with other types of building. Moreover in hospital building some of the lighting loads and other loads are very critical and it is compulsion to supply them through UPS system. Use of AC-DC hybrid supply system can eliminate the rectification and inverter losses within UPS system resulting high chances of energy saving. So this study has been carried out by taking Helping Hands Community Hospital Chabahil-Kathmandu as a reference hospital building.This study also focuses on the development of wiring model for hybrid AC-DC system for a specified building.

2. Research Methods

2.1 Data collection and Load survey

Data regarding to number and types of fixtures used and their respective load has been collected through load survey by direct observation and data regarding to distances between circuit point to DB point to main distribution board (MDB) point has been measured with the help of architectural drawing of the building.

In an existing supply system all types of load were fed from 500 kVA transformer. Now for this work AC circuit, Power socket circuit, X-ray machines, lift motor and OT light is assumed to be supplied from AC line and remaining lighting fixture and fan is will be feed from DC line. Total number of various lighting fixture and their respective power ratings has been identified and are listed on table 1. Details of measured distances of distribution boards (DBs) from main panel and total DC load per DB is identified and are listed in table 2 and distances of lighting circuit points from distribution boards (DBs) and total DC load per lighting circuit points are also identified.

Table 1: Number and power ratings of different load

TYPE OF LOAD	Total Number	TOTAL LOAD (Watt)
LED tube light (18 watt)	578	10404
Mirror light (10 watt)	36	360
Dome light (8 watt)	83	664
OT light (50 watt)	5	250
X-ray view board (15 watt)	25	375
Fan (60 watt)	35	2100
Computers (100 watt)	27	2700
A/C circuit	50	60000
Power circuit (with 0.2 Demand factor)	104	62400
X-ray Machine	1	51000
X-ray Machine	1	36000
Lift	1	6700
10 kVA UPS	1	
Total Load (kW)	232.953	
Total lighting load that can be replaced by DC (kW)	16.853	

2.2 DC wiring model development

2.2.1 Voltage level selection

Selection of low voltage will cause the higher current to flow means need of large size of wire and breaker for same load compare to that for high voltage. Where as selection of high voltage is restricted due to unavailability of low power consumption devices like LED lights at high voltage. Mostly commercial DC LED lights and fans are available in 12V/24V and 48V, DC system of 48V has been selected.

2.2.2 Wire size selection

For 48V DC system size of the wire is firstly selected based on the current carrying capacity of wire as provided by the product catalogue of the wire manufacturer company (for reference product catalogue of Lumbini Vidyut Udyog Pvt. Ltd. is considered) and then voltage drop for respective wire size has been calculated using $\Delta V_{dc} = 2RP/V_{dc}$ where, ΔV_{dc} is voltage drop in DC system, R is resistance of wire, P is load power and V_{dc} is DC system voltage. Calculated value of voltage drop is then compared with allowable voltage drop, if it is within allowable limit, selected wire size is correct if not increased value of wire size has been chosen and again voltage drop for respective wire size has been calculated until voltage drop limit of desire value is obtained.

According to National Electrical Code (2011), allowable voltage drop between the origin of the installation (usually the supply terminal) and the fixed current using equipment should not exceed 4 percent of the normal supply voltage. For this project length between supply terminals to fixed current using equipment is divided into three section.For section between lighting circuit points to respective fixtures existing 2.5 sq.mm copper flexible wire (DC resistance of 0.00887 Ω/m as per reference catalogue) can be used in which voltage drop is negligible (about 0.1 percent for up to 20 meter length). Allowable voltage drop of 2 percent each is assumed for wire section between distribution boards to the respective lighting circuit points and for wire between main distribution board to distribution boards where new cable has to be installed.

Based on the above information and the calculation the size of the wire for each segment has been selected.For section between lighting circuit points from respective DBs 476 meter of 2.5 sq.mm wire, 249 meter of 4 sq.mm wire and 223 meter of 6 sq.mm wire is required and for section between DBs from MDB wire size required is shown in table 2.

Table 2: Size of wire required to supply DC load to DBs from MDB with voltage drop limit of 2 percent.

A	DB number
B	DC load per DB (watt)
C	Selected wire size (sq. mm)
D	DC resistance of wire at 80°C (0.001Ω /m)
E	Distance of DBs from MDB (meter)
F	Voltage drop (percentage) with 20 percent extra load consideration

A	B	C	D	E	F
DB-0	756	6	4.07	8	1.7
DB-1	4793	50	0.476	15	2.4
DB-2	2206	35	0.68	19	2.0
DB-3	1652	35	0.68	23	1.8
DB-4	1614	35	0.68	27	2.0
DB-5	1982	50	0.476	31	2.0
DB-6	1918	50	0.476	35	2.2

2.2.3 Fuse size selection

Although 48V DC does not require any protection against direct contacts [6] protection system for lighting circuit protection is essential. For this work fuse of current rating 25 percent more than the full load current is preferred.

2.3 Simulation model development

Converter and controller required to operate AC- DC hybrid system is designed and is modeled and simulated in PLECS (Piecewise Linear Electrical Circuit Simulation) software.

2.3.1 Design of AC to DC converter

Since building has three phase supply and tapping of load of about 15KW from single phase supply will cause the unbalance of the system. So three phase full bridge rectifier has been used. For phase voltage $V_P = 220V$ output DC voltage of three phase full bridge rectifier is ($V_{dc\ avg} = 2.338V_P$) 514.36 V and for DC load of 15kW $I_{dc\ avg} = 29.16Amp$. So power diode (1N1190 with repetitive Peak Reverse Voltage $V_{RRM} = 600V$, continuous forward current $I_F = 35A$, diode forward voltage $V_F = 1.2V$) has been selected that satisfy the voltage rating and current rating as calculated above. Due to the voltage drop of 2.4V ($= 2 \times 1.2V$) in practical diode the actual output voltage will be about 512V.

2.3.2 Design of L-C Filter

Pulsuating DC output voltage from rectifier is smooth out using Inductor-Capacitor (L-C) filter where capacitor helps to smooth out the voltage pulse and inductor helps to smooth out the current pulse. To design L-C filter, value of capacitor is chosen to be 25 percent of the value which is needed in order to reduce the output ripple within allowable value (about 3 percent) when used alone in the filter circuit (capacitor filter circuit only) and then value of inductor is selected randomly until output ripple factor will obtained within 3 percent [7]. The output ripple factor can be obtained from [7]

$$RF = \frac{0.707 \times Peak\ ripple\ voltage\ (V_p)}{Average\ DC\ output\ voltage\ (V_0)}$$

Value of capacitor needed to reduced the ripple within allowable limit when used alone in the filter circuit can be calculated from $RF = 1/[\sqrt{2}(2f_rRC - 1)]$ Where, C is the required value of capacitance (F), RF is the

allowable ripple factor (about 3 percent), R is load resistance (Ω) and f_r is the output ripple frequency (= 2× frequency of AC source) [8].
Using this approach value of inductor and capacitor required to limit the ripple factor within 3 percent are found to be 10 μH and 1000 μF respectively.

2.3.3 Design of DC-DC converter

The rectified output voltage of 512V DC is step down to 48V DC using buck converter. Buck converter has been designed for input voltage $V_s = 512VDC$, output voltage $V_0 = 48VDC$, Load power $P = 15kW$, Switching frequency $f_s = 100kHz$ and Output voltage ripple factor $= 1 percent$ by calculating other parameters required as below-

$Duty\ cycle(D) = V_o/V_s = 0.09375$
$Average\ load\ current(I_{avg}) = P/V_o = 312.5A$
$Load\ Resistance(R_L) = V_o^2/P = 0.1536\Omega$
$Inductance(L) = V_0^2(1-D)/2P_{min}f_s = 10\ \mu H$
$Capacitance(C) = V_0(1-D)/8L\Delta V f_s^2 = 1618\mu F$
$PWM\ Frequency = f_s/D = 1066.67kHz$

Using above calculated parameter rectifier and buck converter circuit (for open loop system) has been designed.

2.3.4 Design of close loop DC-DC Buck Converter

Closed loop control system has been designed using two loop average current control approach with PI controller in order to regulate the output voltage and current. Block diagram of complete two loop average current control system is shown in figure 1. In outer voltage control loop output voltage is compared with a preset reference voltage and resulting error signal is processed through PI controller to generate reference inductor current signal which helps to regulate the output voltage. In inner current control loop inductor current which is tuned by adjusting duty cycle of the switch is compared with the reference inductor current signal. The final control signal is feed to the PWM generator in order to control the switch. Parameters of PI controller ($K_p\ and\ K_I$) has been estimated using bode plot.

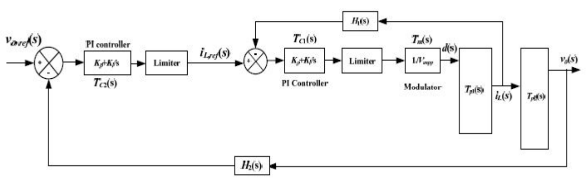

Figure 1: Two loop average current control [9]

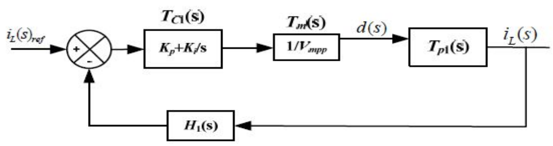

Figure 2: Block diagram of inner current loop [9]

In current loop parameters of PI controller has been estimated for achieving stability criteria. To design controller, duty cycle to inductor current transfer function $T_{P1}(s)$ is derived from small signal analysis by neglecting ESR of inductor and capacitor and is given as, [10].

$$\frac{i_l(S)}{d(S)} = \frac{V_I(1+R_LCS)}{R_LLCS^2+LS+R_L} = \frac{5.5\times10^8(S+3255)}{S^2+3300S+5.12\times10^7}$$

From bode plot of [TP1(s)] phase margin of 90° is obtained at cross over frequency ($\omega_c = 550Mrad/sec$).

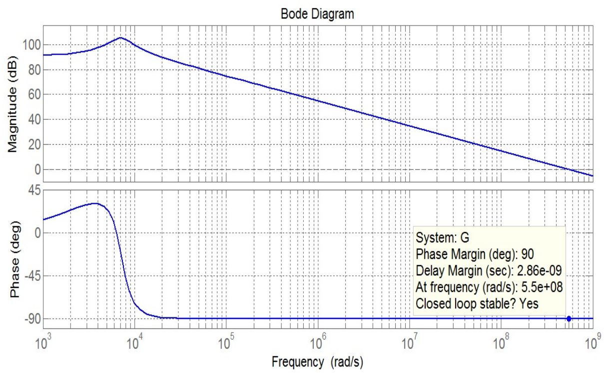

Figure 3: Bode plot of transfer function $T_{P1}(s)$

For current loop feedback gain $[H_1(s) = 1]$, modulator transfer function $[T_M(s) = 1]$ and transfer function of PI controller $T_{c1}(S) = T_{c2}(S) = K_p + K_i/S$, open loop transfer function for current loop $[T_{OL1}(j\omega_c)]$ will be,

$$T_{OL1}(j\omega_c) = \frac{1750K_p(j314000+\frac{K_i}{K_p})(j314000+3255)}{-j9.85\times10^{10}-1.036\times10^9}$$

PI controller has been designed to have 60° phase margin of open loop system at the gain cross over frequency of 314 k rad/sec. Using gain and phase angle condition ($|T_{OL1}(S)| = 1$) and ($\angle T_{OL1}(S) = PM(60°) - 180°$) at cross over frequency ($\omega_c = 314krad/sec$), parameters $K_p = 0.0005$ and $K_i = 90$ has been obtained.

For voltage loop, to design controller inductor current to output voltage transfer function $T_{P2}(s)$ is derived

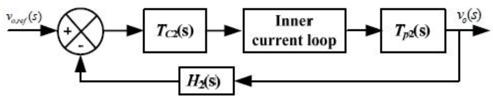

Figure 4: Block diagram of outer voltage loop [9]

from small signal analysis by neglecting ESR of inductor and capacitor and is given as [10].

$$\frac{V_0(S)}{i_l(S)} = \frac{R_L}{(1+R_LCS)} = \frac{0.1536}{(1+3.072\times10^{-4}S)}$$

From bode plot of $[T_{P2}(s)]$, the system for voltage control loop is found to be unstable.

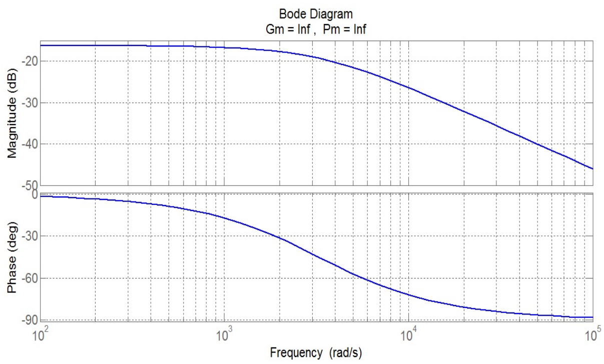

Figure 5: Bode plot of transfer function $T_{P2}(s)$

Now a PI controller as a compensator is designed maintaining minimum phase margin of 60° at $\omega_c = 6.283krad/s$. Inner current loop being faster than the outer voltage loop the inner current loop dynamics can be neglected in the voltage loop design [9]. For output voltage reference of 10 V, feedback gain $H_2(S) = 0.208$, open loop transfer function of the voltage loop can be expressed as,

$$T_{OL2}(j\omega_c) = \frac{0.0165K_p(j6283+\frac{K_i}{K_p})}{j3252-6283}$$

As in current loop $K_P = 36.7$ and $K_I = 360216$ has been obtained using gain and phase angle condition.

Using all the calculated parameters, a complete closed loop controlled buck converter has been modeled in PLECS as shown in figure 6.

3. Results and Discussion

3.1 Simulation Results

The designed closed loop model has been simulated on PLECS for estimated value of PI controller parameters and for closed loop system overshoot of 84 percent

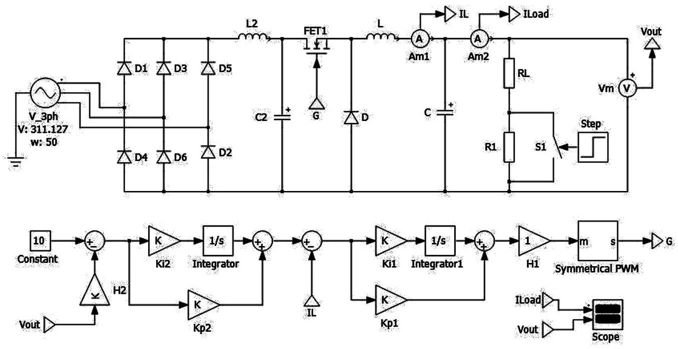

Figure 6: Complete closed loop controlled buck converter simulation model in PLECS

and oscillation has been observed which is needed to be improve. This can be improved by decreasing value of proportional gain constant and/or integral gain constant. In order to improve the response PI controller parameter of voltage loop has been manually tuned by decreasing $K_{P2}$to 9.175 and K_{I2} to 36021 which almost eliminates the overshoot and oscillation and results the output voltage of 48V with voltage ripple below designed criteria of below 1 percent. Waveform of output voltage after tuning is shown in figure 7

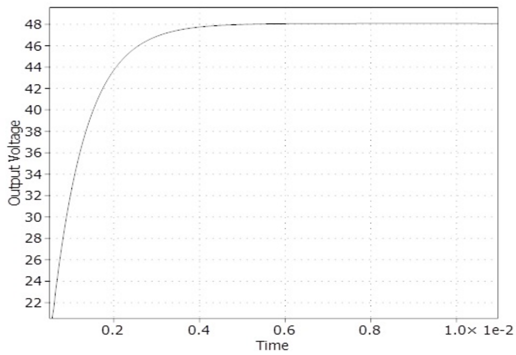

Figure 7: Waveform of output voltage

Output of converter model has been simulated in PLECS for 10kW, 15kW and 20kW load by modeling 0.2304Ω, 0.1536Ω and 0.1152Ω resistor respectively. Waveform of load current and voltage for all three load level is shown in figure 8. For 10kW load simulation a current of 208A with constant voltage of 48V has been observed. When load is increased to 15kW and 20kW load current is increased to 312.5A and 416.5A however voltage is maintained at constant value of 48V which shows modeled converter properly regulates the voltage to a constant level of 48V.

Waveform in figure 9 shows the response of load current and voltage for step change in load from

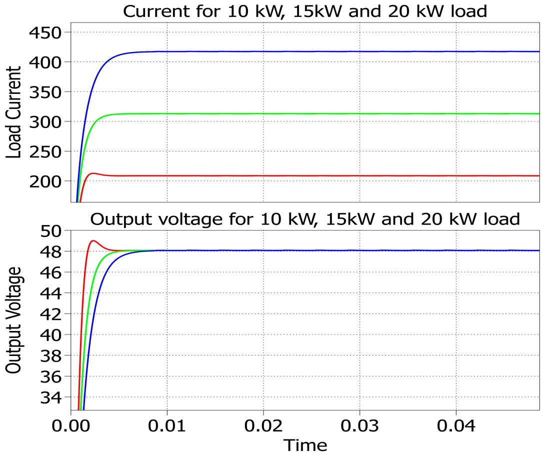

Figure 8: Current and Voltage waveform for 10kW, 15kW and 20kW operating load conditions

15kW to 20kW after 0.3 second. Initially 15kW load has been simulated, after 0.3 sec step load change from 15kW to 20kW has been made. As shown in the waveform of figure 9 for 15 kW load current is 312.5A at voltage level of 48V. After 0.3 sec when load is suddenly increased to 20kW, voltage level attains a negative overshoot of about 8V and attains steady level of 48V after 3.5 ms. Voltage overshoot is negative due to sudden addition of load and for sudden decrease in load overshoot will be positive. Amount of overshoot depends on magnitude of load added or removed. For higher amount of sudden load changed overshoot will be more and for gradual change in small amount of load overshoot will be small. From simulation for step load change of 500W, voltage overshoot was only 0.8V.

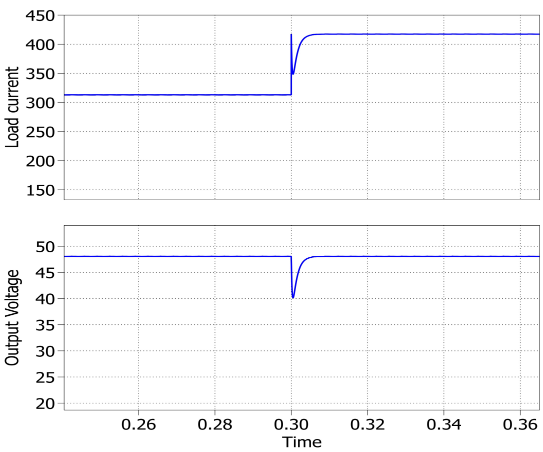

Figure 9: Response of load current and voltage for step load change from 15kW to 20kW

3.2 Efficiency evaluation of converter model

Overall efficiency of converter model has been evaluated by calculating the power losses in rectifier, filter and buck converter circuit.

For 15kW load simulation $I_{out\ rectifier} = 30A$, $I_{rms\ inductor} = 313A$, $I_{rms\ FET} = 97A$, $I_{rms\ diode} = 298A$ is measured as a result , $R_{on}(diode) = 0.034\Omega$ from datasheet of 1N1190 diode, DCR of $10\mu H$ Inductor $= 2.4m\Omega$ from datasheet of WURTH ELEKTRONIK 744364100 model and $R_{DS\ ON} = 66m\Omega$, total gate charge $(Q_g) = 190nc$, output capacitance $(C_o) = 3200PF$, rise time $(t_r = 160ns$, fall time $(t_f) = 120ns$, gate voltage $(V_{drive} = 10V\ maximum$ from data sheet of FCH47N60F-F085 has been used and losses were calculated as below-

$P_loss(Rectifier) = 2 \times I^2_{out\ rectifier} \times R_{on} = 61W$
$P_loss(Filter) = I^2_{out\ rectifier} \times DCR = 2W$
$P_{loss}(Inductor) = I^2_{rms\ Inductor} \times DCR = 235W$
$P_{loss\ conduction}(FET) = I^2_{rms\ FET} \times R_{DS\ ON} = 621W$
$P_{loss\ by\ gate\ charge} = 0.5Q_g \times V_{drive} \times F_{SW} = 0.095W$
$P_{loss\ by\ FET\ capacitance} = 0.5C_o \times V^2_{in} \times F_{SW} = 42W$
$P_{loss}(during\ t_r, t_f) = \frac{(t_r+t_f)}{2} I_{rms\ FET} V_{drive} F_{SW} = 14W$
$P_{loss}(diode) = I_{rms\ diode} \times V_F = 238.4W$
$P_loss(Total) = 1213.5watt$

Neglecting some losses like; loss due to capacitor ESR, diode recovery loss and inductor core loss which are negligible for low frequency switching overall efficiency of DC system components is found to be 92.5 percent for 15kW of output power.

3.2.1 Energy saving and Sensitivity analysis

To evaluate energy savings, areas of hospital building were categories based on daily turn on hours of lighting, fan and computer load. In passage, stair, toilet areas all lighting fixtures are estimated to be turned on for 12 hour and 50 percent of them are turned on for next 12 hour. In areas like nursing stations, wards, cabin, ICU, pharmacy all lighting fixtures are estimated to be turned on for 12 hour and 50 percent of them are turned on for next 12 hour. In operation theater area all lighting fixture are estimated to use for 10 hour. In areas like OPD, doctor's room, administration area 50 percent lighting fixture are estimated to use for 8 hour. In rooms like x-ray, USG, ECG etc all lighting fixture are estimated to use for 8 hour and 50 percent lighting fixture are estimated to use for another 8 hour. In sterilization area all lighting fixture are estimated to use for 10 hour. In areas like store, changing, utility etc all lighting fixture are estimated to use for 3 hour. Similarly, computers and fan in nursing stations are estimated to use for 12 hour and in administration for 8 hour.

Energy saving has been evaluated based on the efficiency improvement options carried out in past researches. From past research, DC based LED driver are 10 percent more efficient than that of AC based LED driver [11] . That means if AC LED lights were replaced by equivalent DC LED lights, 10 percent energy can be saved. Similarly DC based computer charging system are 4.25 percent more efficient than AC based charging system and DC fans are 24 percent more efficient than AC fans [12] and for UPS with 90 percent efficiency and for full load operation 8 percent energy can be saved with elimination of rectification process and inverter with in UPS [13].

Evaluation shows that for above mention operation hour and operating load condition 20kWh energy can be saved per day. However operation time and operating load condition being uncertain chances of energy saving being 20kWh is also uncertain. In order to know about the certainty and sensitivity of energy saving due to variations in parameters like operation hour and operating load condition simulation has been done in Crystal Ball software. Simulation has been carried out for 25 percent less variation in operation hour of equipments, minimum 50 percent to maximum 100 percent of load supply conditions through UPS and 4 percent to 8 percent improved efficiency condition of UPS due to elimination of rectification and inverter process.

Figure 10 and figure 11 shows the simulation result of crystal ball about certainty of energy saving. Simulation result shows that there is 99.69 percent chance of energy saving being more than 13.5 kWh, only 11.23 percent chance of energy saving being more than 20kWh and there is no chance of energy saving being more than 22.67 kWh.

Sensitivity on energy saving variation is shown in figure 12 which shows that improved in UPS system efficiency due to elimination of rectification and inverter process (indicated by H40) and percentage of load supplied by UPS (indicated by H39) are the major factors for variation in energy saving and operation hour of fans (indicated by F19 and F13) has minimum impact of about 1.4 percent whereas operation hour of lights have negligible impact on variation in comparison to other factors.

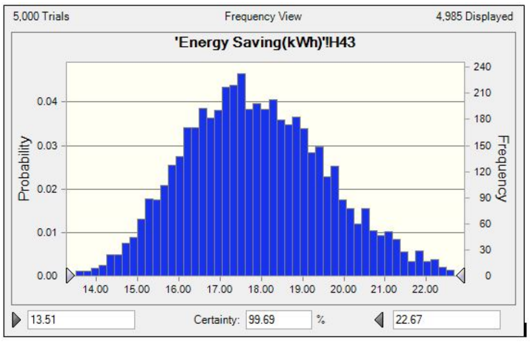

Figure 10: Simulation result of crystal ball about certainty of energy saving

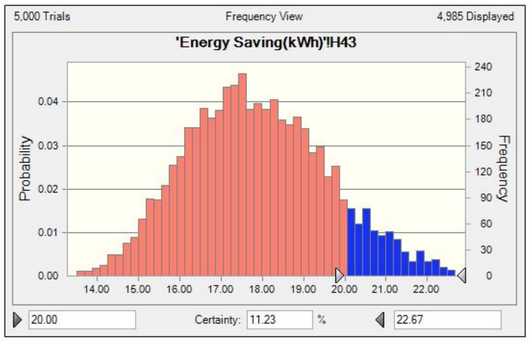

Figure 11: Simulation result of crystal ball about certainty of energy saving being more than 20kWh

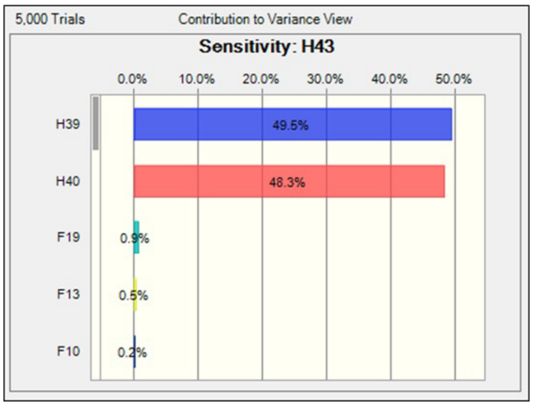

Figure 12: Simulation result of crystal ball about sensitivity of parameters on energy saving variation

4. Conclusion

From simulation result it can be concluded that AC-DC hybrid supply system could be the option to save electrical energy consumption in a hospital building. However amount of energy saving is found to be highly dependent on saving factors like amount of load that can be replaced by DC load, amount of load supplied through UPS system and hour of operation. Energy saving due to replacement of only AC lighting fixture by DC fixture is found to be less effective due to losses in the rectifier and DC-DC converter model required to create DC line in a building. But integration of such fixture in large scale could make it effective. However incorporation of online UPS in the evaluation which is compulsory in use for hospital buildings enhances the energy saving opportunity with the elimination of rectification and inverter process.

To implement hybrid supply system for building same wire that were in use for AC system can be use to supply load from distribution boards to end use consumption point. But to maintain voltage drop size of cables for supply to distribution boards from main distribution board has to be increased. Because of the replacement needed for some cables section, load fixture and necessity of converter model financial feasibility will become the question for upgrading an existing building.

Future Enhancement

In future with a possibility of power distribution system being advanced with hybridization and bidirectional energy trade system, hybrid supply system for building by replacing backup DG by solar PV system to enhance building efficiency (by eliminating rectification process needed to make DC supply line) as well as energy trade could be a topic for further study.

Research can be done further for a cluster of residential area together by making hybrid supply system for secondary distribution by converting AC to DC at distribution transformer point to develop DC line for hybrid system and making facility to interconnect individual solar home system to DC distribution line.

Acknowledgments

The authors are grateful to MSESPM Program, Department of Mechanical Engineering Pulchowk Campus for providing the opportunity and support for this research and thankful to Helping Hands community Hospital, Chabahil for allowing to conduct survey in such a critical place.

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