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Design for a Grid-integrated, Renewable Power Supply for Traffic Control Systems

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Abstract—*Traffic lights are signaling devices positioned at road intersections, pedestrian crossings and other similar locations. They are used to control conflicting traffic flow. Traffic signals are an essential asset especially in the African society with its large population and poor driving ethics. The need for this work stems from the recent instances of power outage widely experienced in the country. Loss of power supply has led to frequent interruption in the operation of traffic control systems dependent on grid power. This project aims to study the severity of the situation and design a reliable supply system that would eliminate these interruptions. The stated aim will be achieved by obtaining and analyzing power supply data from the power holding company supplying the test location and then using the insights from that analysis to design a renewable energy based backup system. For this project, power outages are analyzed using a probability model. The power outage durations which are measured and presented as continuous variables are discretized by grouping them into ranges in a frequency distribution table. Each range is considered as an independent event thereby allowing for the evaluation of their individual probabilities. After the individual probabilities of each outage event is determined, the compound probabilities are calculated. Compound probability is the probability of joint occurrence of 2 or more events. This would provide valuable insight into the state of power supply for the test location to aid in the design of the system proposed in this project, policy making and further research.*

Keywords—*Traffic lights, Power outage, Electricity company of Ghana, data analysis, Kasoa intersection.*

I. INTRODUCTION

In Ghana, Power is conventionally supplied to traffic control systems from the national grid. As a result of recent developments such as aging infrastructure, and poor maintenance culture, the power system of the country has experienced reduction in its generating capacity. Also, the yearly rise in population has caused an increase in load magnitude. This reduced supply and increased demand has created a need for load shedding.

Aside from the mismatch between demand and supply, the deteriorating state of the system has also led to frequent occurrence of fault situations which trigger protection system action and subsequently causes power supply interruption.

These are some of the factors responsible for the unreliable state of power supply in the country.

Traffic lights are signaling devices which alternate the right of way accorded to road users by displaying lights of a standardized color code (red, yellow and green). The operation of these lights is governed by a control system as it implements a code whose algorithm is designed to control the associated flow of vehicles.

Whenever an outage occurs on the distribution network to which a grid-dependent traffic control system is connected, it experiences a loss of power supply. Its operation ceases causing what is known as a dark signal. Basically, this refers to a situation where the lights on the signal heads go off. As a result, control of the associated traffic of vehicles is lost.

Furthermore, the components which comprise the traffic control system are sensitive to abnormal voltage fluctuations as is the case at times when power is restored following an outage. This abnormal voltage fluctuation can cause damage to system components.

This project is focused on studying the reliability of power supply to traffic control systems in the case location.

II. LITERATURE REVIEW

The most common power supplies for traffic control systems is the direct to grid connection. This supply strategy depends on the grid as the primary and only power source.

Problems Associated utility grid power supply

1) Reliability**:** The dependence of this design on the grid makes such systems susceptible to loss of power supply whenever an outage occurs on the distribution network to which they are connected [6]. This outage can occur as a result of:
- Load shedding.
- Fault situations
2) Quality of power supply: The dependence of this design on the grid makes it vulnerable to changing power quality characteristics prevalent on the grid such as:
- Voltage fluctuation.
- Harmonics, etc.

These adverse grid power parameters can cause damage to system components.

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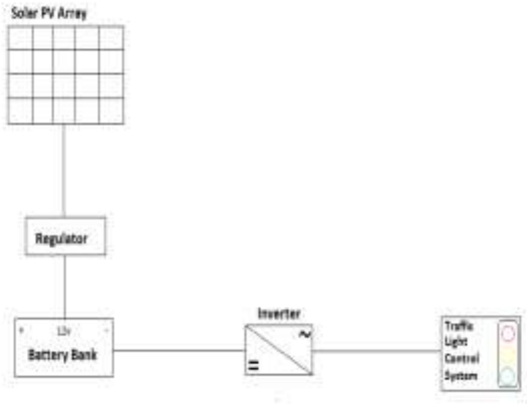
The poor reliability and quality of power from the utility grid has created a need for innovative power supply designs with backup power sources to support the grid in order to ensure reliable and quality power supply to vehicular traffic control systems.

Driven by the need for improved reliability or reduced cost, several power supply designs have been adopted. Their individual strengths and weaknesses are reviewed in this chapter.

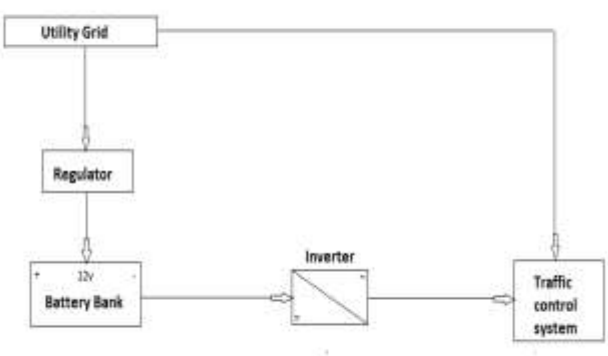
2.1 Solar PV system with battery backup



Fig, 1.1 Diagram of the solar PV design with battery backup

Fig. 1.1 refers to a stand-alone solar PV system. It incorporates a solar PV array along with backup batteries in a setup such that the PV array charges the battery and the battery powers the traffic light control system. The system is usually designed to be self-sufficient hence often referred to as the "autonomous solar PV system." The operation of this power supply is similar to the operation of solar power generation systems conventionally used to power off grid residential homes. The autonomous solar PV design is suitable for locations which are far away from electrical distribution networks. The main disadvantage of this design however, is its dependence on the sun as this makes it unreliable during bad weather conditions. For certain climates, where bad whether causes insufficient sunlight, this design was found to be a high cost solution as a large specification of battery capacity was required to cater for extended periods of stormy weather [6].

2.2 Utility grid connection with battery backup



Fig, 1.2 Diagram of the utility grid supply with battery backup

The supply strategy illustrated in Fig 1.2 refers to the addition of a battery bank and an inverter to the circuitry of a signalized intersection to allow the traffic light control system run on battery power in the event of a grid power outage. Most of the current reported BBS (battery backup systems) include batteries that are charged by utility power to be used as a backup source when power outage occurs. The switch over from utility power to battery power typically occurs within milliseconds causing little or no noticeable interruption in signal operations. For this reason, they are often referred to as UPS (uninterruptible power supply) [6:6].

Traffic control systems with this power supply configuration depend on the grid as the primary power source to feed the load and also float charge the batteries. The main advantage of this supply strategy is its Low-cost relative to other backup power supply designs considered in this project. During periods of extended outages however, the batteries run out, power supply to the traffic control system is lost and the signal heads go dark. For this reason, this design is not reliable during periods of extended power outage.

The idea behind the power supply choice for this project is to create a power supply system which has the desirable attributes of each of the reviewed designs. These are reliability and low cost which are the desirable attributes of the autonomous solar PV system and the UPS system respectively. The power supply choice for this project is the grid-integrated solar PV system. It is a hybrid of the two reviewed designs and consist of components from each, as a result, possess characteristics of each design.

III. METHODOLOGY

The idea employed in this project is inspired by the energy and cost-efficient concept of Renewable energy - Grid integration. Solar energy is used to feed base-load during daylight hours instead of storing it in batteries while fuel is stored to be used during peak load. Relative to electrical energy storage in batteries, fossil fuel storage is significantly less expensive. This ingenious technique virtually serves the purpose of the battery at a lower cost. This project is aimed to adapt this design philosophy to traffic control power supplies.

The innovative contribution made by this project is the use of the outage statistics and load shedding schedule for chosen location to predict outage time and duration. To do this, the fault history of the chosen location is analyzed statistically to determine:

1) The time within the 24-hour period of day when the grid is most prone to outages.
2) The resulting outage duration.

Accurate prediction of outage time and duration would enable better allocation of design assets to address the inadequacies of grid supply. It will also eliminate the arbitrary sizing approach frequently used which often leads to over-sizing which is expensive or under-sizing which would make the system inadequate and thus unreliable.

These pieces of information are used to more accurately predict outages and therefore, devise a supply plan which would economically provide backup reinforcement for the

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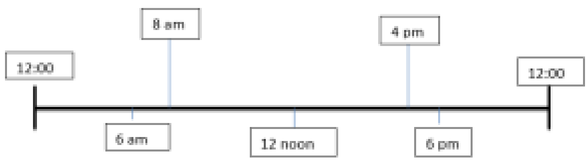
predicted outages and thereby ensure cost efficient reliable power supply.

Proposed supply strategy

Haven reviewed the UPS and autonomous solar supply technologies in the previous chapter, the supply strategy proposed for this project involves the integration of the grid and a solar array. The solar array acts as the primary source to provide power during daylight hours (8am – 4pm) while the grid acts as the primary source which provides power at every other instance. Backup batteries are included to prevent loss of power supply to the system during grid power outages.



24 hour power supply plan

Fig 3.1 is a timeline which shows the supply schedule associated with the proposed power supply design. With this timeline power from the various sources can be rationed such that the power supply system is reliable and cost efficient.
8am – 4pm: During this period of day, the sun is available therefore solar power is used to power the traffic control system while power from the grid is used to charge the batteries.
4pm – 8am: The grid is the primary source at every other instance. A battery bank is included to provide backup power supply for grid power outages within this period.

Implementation of objectives

In this section, a case study of a traffic intersection in the kasoa metropolitan area is considered. The consideration of a location in this case study makes it possible to obtain several parameters required for component sizing such as:

1) Type of intersection - Based on the number of roads which meet at the intersection. This helps to determine the number of signal heads required. This information is used for the load estimation.
2) Daylight hours and solar intensity- Based on the climatic condition of the chosen location. This information is used for the PV array sizing.
3) Outage frequency and duration - based on the power shedding schedule and fault occurrence statistics obtained from the utility company for the feeder suppplying the test location. This is used to estimate the autonomy time which is required for the battery capacity and PV array sizing.

The above information is used to associate the designed system with real time traffic control operation.

First objective: Estimate power consumption of the traffic control system.

Traffic control systems consist of 3 main parts

1) Signal heads.
2) Vehicle detector loops and pedestrian push buttons (for closed loop systems).
3) Controller.

To estimate the power consumption of the traffic control system, the following were considered:

1) *Power consumption of the signal heads*

For this project the LEDs are employed as they are more energy efficient and durable.
LED TECHNOLOGY

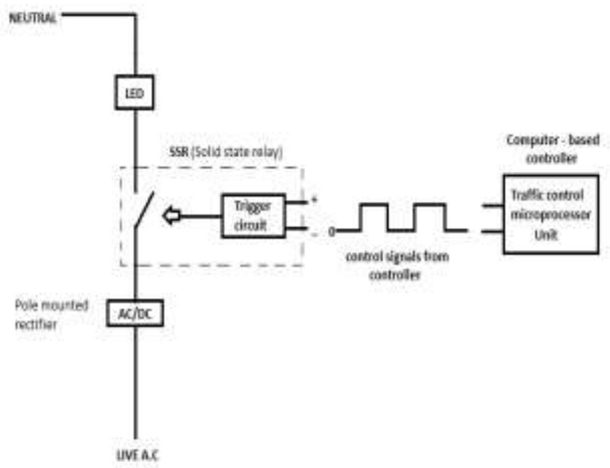


Figure 3.1 LED traffic control technology

The power rating of a 300mm LED vehicular signal lamp is approximately 30watts (per aspect) therefore, a 3 aspect signal head would have a power rating of approximately 90watts [17].

2) *Number of signal heads.*

This is based on the type of intersection considered in the case study.

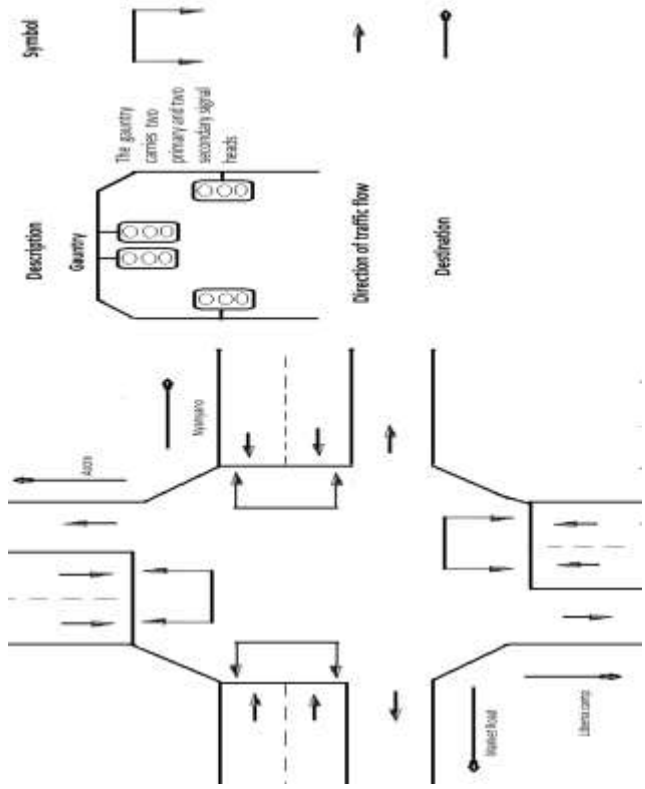


Fig. 3.2. Kasoa main intersection (before construction of fly over)

At each double lane road a gantry carrying four signal heads(two primary and two secondary) is erected. Four double lane roads meet at the intersection, as a result, 4 gantries are required hence, a total of 16 signal heads are used.

Each combination of green and red signals the controller is programmed to display is called a phase.

Per phase wattage = no. of lamps switched on per phase x power rating of each lamp.

1 lane is allowed to move per phase thus per phase wattage

= (4reds per lane x 3lanes + 4 greens) x 30W = 16 lamps x 30W = 480W.

Power consumption of signal heads = (per phase wattage + 10%)

= 480W +48W

= 528W

3) *Power rating of controller:* The power rating of the chosen traffic signal controller is stated at 60 watts.
4) *System efficiency:* System efficiency accounts for copper Losses in the conductors and battery round trip efficiency. A standard factor of 1.2 is used in the load estimate equation to account for inefficiencies in the system [5].

Hence the power consumption/load estimate of the intersection

= (power consumption of signal heads + power rating of controller) x system efficiency factor.

Power rating of Signal heads = 528W.

Power rating of Controller =60W.

System efficiency factor = 1.2.

Therefore, load estimate = (528 + 60) x 1.2 = 705.6W.

Second objective: Estimate outage duration

A probability model is a mathematical representation of a random phenomenon. It is defined by its sample space, events within the sample space and probabilities associated with each event. For the purpose of this project, a probability model is used to analyze the recorded monthly power outage durations for the feeder serving the traffic light control system.

The sample space is a set of all possible ranges of outage duration from the given statistical data. The events are the durations of each individual outage instance and the probability model is used to obtain the probability of occurrence of each event.

Recorded Monthly Power Outage Durations for Kasoa / Tuba feeder.

TABLE 3.1 Recorded outage durations [14]

Month	Planned (maintenance) (mins)	Unplanned (fault) (mins)
January	43.2, 141, 16.8, 6.0, 10.2	424
February	0	0
March	85.8, 19.2, 19.2, 19.8, 36	121.8, 7.8

Outage durations as shown in table 3.1 are unsymmetrically distributed. For ease of calculation they are discretized by categorizing them within ranges as shown below in table 3.2.

After the outages are categorized in ranges, each range becomes an event. Therefore, the probability of each event, the compound events (combined events represented as $p(n) \cup p(n)$ and cost in terms of battery capacity are calculated and tabulated as shown below in table 3.3.

TABLE 3.2 Outage frequency table

Outage duration range (mins)	Outage Frequency	Cumulative frequency
1 – 30	5	5
31 – 60	3	8
61 – 90	1	9
91 – 120	0	9
121 – 150	2	11
151 – 180	0	11
181 – 210	0	11
211 – 240	0	11
241 – 270	0	11
271 – 300	0	11
301 – 330	0	11
331 – 360	0	11
361 – 390	0	11
391 – 420	0	11
421 – 450	1	12

TABLE 3.3 Outage statistics

Let p (n) = probability of outage for (n) minutes.	% of outages accounted for by sizing for outages within the range of (n) (Y)	Cost in terms of battery capacity (Ghc)	RANK (Z)
P (30) = $5/12$	P (30) x 100 = 42%	16,800	4TH
P (60) = $3/12$	$[p(60) \cup p(30)]$ = 66%	33,775	3RD
P (90) = $1/12$	$[p(90) \cup p(60) \cup p(30)]$ = 75 %	50,652	2ND
P (150) = $2/12$	$[p(150) \cup p(90) \cup p(60) \cup p(30)]$ = 92%	84,350	1ST
P (450) = $1/12$	$[p(450) \cup p(150) \cup p(90) \cup p(60) \cup p(30)]$ = 100%	253,330	5TH

Outage duration estimate is used to size backup battery capacity. The outage durations seen in table 3.2 are unsymmetrically distributed over wide ranges (i.e large differences in duration among various outage instances) hence, the idea of an optimal outage duration estimate would be the "shortest outage duration which accounts for the most outage instances", as this would be the most reliable and cost effective option for use to size power generation and storage components.

The index of table 3.3 shows, how the various compound outage durations compare in terms of length and percentage of outages accounted for, in other words, cost and reliability. This is used to index/score the various outage scenarios. The compound outage duration with the highest index score is then used as the autonomy time required for the power supply design in this project as this ensures the highest reliability at the lowest cost.

3.81Estimated Outage duration: The estimated outage duration used when sizing components for the proposed design is given by the outage duration corresponding to the highest value of (Z) (i.e highest outage durations accounted for (Y) per dollar (Ghc)).From table 3.3, this is seen to be the outage duration corresponding to 1STon the Z column = 150

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minutes. Therefore, estimated outage duration = 2hours 30 minutes.

3.9Third objective: size PV array

Number of PV modules required (N) is expressed as

$$N = \frac{E_d \times f_o}{P_{mod} \times G \times \eta_{pvss}} \text{......................(1)}$$

Where

E_d is the design energy = load estimate x no. of hours used =705.6w x 8 hours(8am-4pm)= 5.64 kwh.

f_o is the oversupply coefficient = 1.3 p.u (standard factor).

P_{mod} de-rated power output of the PV module = name plate rating x de-rating factor

=200w x 0.95

= 190w

G is the solar irradiation for chosen location

G = 4.9 kWh/m^2/day [11]

η_{pvss} is the efficiency of the PV. Sub system (inverter, charge controller etc) = 80%

Therefore, $N = \frac{5640 \, X \, 1.3}{190 \, X \, 4.9 \, X \, 0.8}$

~ = 10 (200w modules).

3.10 Fourth objective: size battery capacity

The minimum battery capacity required for the design load over the specified autonomy time can be calculated as follows:

$$C_{min} = \frac{E_d(k_a \times k_t \times k_c)}{V_{dc} \times k_{dod} \times k_e} \text{......................(2)}$$

C_{min} Minimum battery capacity required

E_d is the design energy = load estimate x autonomy time

=705.6w x 2.5hours

= 1,764VAh

V_{dc} is the nominal battery voltage = 12 Vdc

k_a is a battery ageing factor (%) =1.25

k_t is a temperature correction factor (%) =1.040(at room temperature)

k_c is a capacity rating factor (%) =10%

k_e is a system efficiency (%) = 80%

k_{dod} is the maximum depth of discharge (%) = 80% for deep cycle batteries

$$C_{min} = \frac{1764 \, (1.25 \, x \, 1.040 \, x \, 0.1)}{12 \, x \, 0.8 \, x \, 0.8}$$

= 30 Ah

The storage capacity of a battery is the amount of electrical energy it can hold. This is usually expressed in ampere hours (Ah). E.g for a 100Ah battery, ideally one amp can be used for 100 hours or alternatively 100 amps can be used for one hour.

From the battery sizing equation shown above, it can be seen that battery capacity increases with increase in autonomy time. Also, battery capacity has a directly proportional relationship with the cost of the battery (i.e Cost α AH rating). Therefore, as autonomy time rises, battery capacity also rises and when battery capacity rises so does its cost.

Components are also sized for the various reviewed designs in order to compare them to the proposed design in terms of reliability and cost. The results are tabulated and presented in Table.

For the Grid connected supply with battery backup: A solar PV array is not used. The required battery capacity for this power supply is shown below:

Design energy = load estimate x autonomy time= 705.6w x 2.5hours = 1764VAh

$$C_{min} = \frac{1764 \, (1.25 \, x \, 1.040 \, x \, 0.1)}{12 \, x \, 0.8 \, x \, 0.8} \text{..................... (3)}$$

= 30 Ah.

For the solar PV system with battery backup (autonomous solar PV system): The PV size and required battery capacity for this design is shown below:

Required PV size

E_d design energy = load estimate x no. of hours used = 705.6w x 24hours = 17 kwh.

$$N = \frac{17000 \, X \, 1.3}{190 \, X \, 4.9 \, X \, 0.8} \text{.................... (4)}$$

~= 30 modules.

Required battery capacity

Design energy = load estimate x autonomy time (4pm – 8am (night hours))

= 705.6w x 16hrs = 11.3KVAh

$$C_{min} = \frac{11300(1.25 \, x \, 1.040 \, x \, 0.1)}{12 \, x \, 0.8 \, x \, 0.8} \text{..................... (5)}$$

= 191.3 Ah.

IV. RESULTS AND DISCUSSION

The power supply design proposed by this project consists of two main parts

1) The power generation unit, and
2) The power storage unit.

4.1The power generation unit consists of

1) The solar PV Array.
2) The grid.

4.2The power storage unit consists of

1) Lead acid deep cycle battery.

The power supply design depicted in fig 4.1 uses the grid and a PV array as the primary and secondary power sources respectively. A battery bank is also included to provide backup during grid power outages. In this chapter, the proposed design and the reviewed designs are compared in terms of reliability and cost.

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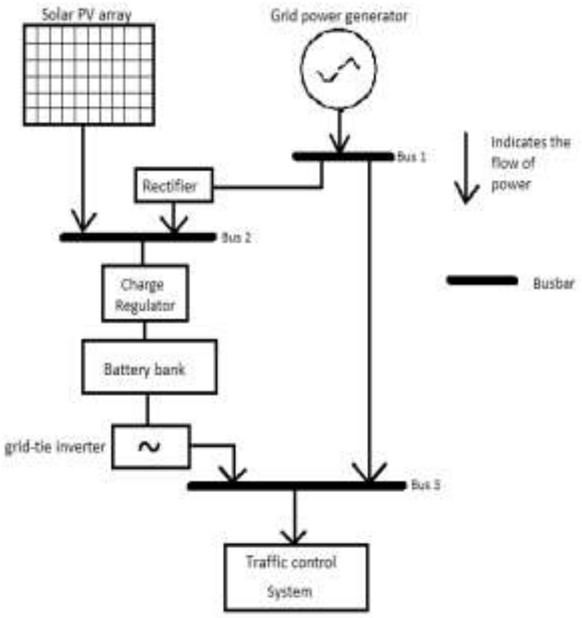

Fig 4.1 Block diagram of the proposed power supply design.

4.3Per unit price of solar PV and lead acid batteries

1) Price per watt of solar PV = $3/watt [15].
2) Price per watt hour of lead acid battery capacity $200/kwh = $0.2/wh[16].

Cost of PV array = (PV name plate rating x number of modules) x price per watt of solar PV.
Cost of battery = (battery capacity (Ah) x battery terminal voltage) x price per watt-hour of battery capacity.

4.4Component specifications

For grid connection with battery backup (UPS): This design does not include PV modules. The required battery size and its cost is shown in table 4.1

TABLE 4.1 Specification and cost of components for UPS systems

Components	Size	Cost
Deep cycle battery	30 Ah	Ghc 302
Total cost		Ghc 302

For solar PV with battery backup (Autonomous solar PV): This design includes PV modules. The size and cost of the battery and PV module are shown below in table 4.2

TABLE 4.2 Specification and cost of components for autonomous PV systems

Components	Size	Cost
PV array	30 modules (200w)	Ghc 75,600
Deep cycle battery	192 Ah	Ghc 1935
Total cost		Ghc 77,535

For the proposed system: This design derives power from PV modules and the utility grid. The sizes for the required components are shown below in table 4.3

TABLE 4.3 Specification and cost of components for proposed design

Components	Size	Cost
PV array	10 modules (200w)	Ghc 25,200
Deep cycle battery	30 Ah.	Ghc 302.4
Total cost		Ghc 25,502.4

4.5 Summary of the various power supply designs

Table 4.4 Cost and backup time comparison for various power supply designs

Design	Cost	Backup time	secondary source
UPS power supply	Ghc 302	2.5 hours	none
Autonomous solar PV Power supply	Ghc 77,535.36	16 hours	none
Proposed power Supply	Ghc 25,502.4	2.5 hours	Solar PV

From the data displayed in table 4.4 it can be seen that

The UPS power supply offers the lowest cost. This can be attributed to its simple design which does not include a PV array. Also, as opposed to the autonomous solar PV system which has a battery bank sized to provide backup power supply for night - hours (4pm -8am (16 hours)), the UPS power supply solely depends on the grid as it's primary and only power source therefore the battery capacity is sized to provide backup power for grid power outages which is estimated at (2.5 hours). This reduction in autonomy time allows for reduction in battery capacity, therefore reduction in cost as well.

During extended outages however, the batteries runs out, power supply to the traffic control system ceases and the signal heads go off. Hence, the UPS design is unreliable during extended grid power outages.

The stand-alone solar PV system often referred to as the autonomous solar PV system relies solely on the solar PV array as its only power source. For the stand-alone design to be reliable, it requires a specification of power generation and storage components which will make it capable of being self-sufficient. This demands the use of a large PV array and battery capacity. The increase in array size and battery capacity leads to increase in cost making this power supply design a high cost solution. Some of the advantages of this design are Immunity from adverse operating conditions prevalent on the grid and reliability.

The proposed power supply provides 2.5 hours of battery backup during grid power outages. Also, a PV array is included to act as a secondary power source. The PV array provides power during extended grid power outages which happen to occur during day – light hours (8am – 4pm when the PV array is generating). Also, this period (8am – 4pm) is within the period when vehicular traffic is at its peak (morning-evening rush hour) according to a survey conducted by (S.wolfgang, Aug 2004) [18], therefore this power supply design ensures the traffic light control systems are functional during this period to facilitate smooth dispatch of vehicular traffic. The inclusion of an alternative energy source makes this design a versatile power supply and improves overall reliability.

V. Conclusion

Power is said to be unreliable when it is frequently interrupted or its quality is degraded as a result of adverse operating conditions emanating from the source or prevalent on the transmission grid. These adverse conditions are

1) Voltage fluctuation.
2) Harmonics.
3) Loss of power supply due to load shedding or fault occurrence.

These conditions can occur as a result of insufficient generation, inadequate transmission or fault occurrence. The stated adverse operating conditions lead to poor power quality or loss of power supply to the distribution network where they occur. The connection of traffic light control systems to the distribution network makes them susceptible to these conditions and can result in the occurrence of dark signals or possible damage to components of the traffic light control system. This situation has created a need for the use of renewable energy technology and backup power sources.

The primary motive of this project is to design a power supply which would allow continued traffic control operation when a grid power outage occurs. This chapter summarizes how this project work achieves this aim and provides recommendations for further studies.

In chapter 2 we review, the two common solutions employed to solve the problem of unreliable power supply to traffic light control systems:

1) Including a battery bank to the circuitry of a signalized intersection.
2) Use of an autonomous Solar PV power system.

In chapter 3, the recorded power outage statistics for the test location is obtained from the utility company and analyzed using a probability model. The outage durations which are measured and presented as continuous variables are discretized by grouping them into ranges in a frequency distribution table. Each range is considered as an independent event thereby allowing for the evaluation of their individual probabilities. After the individual probabilities of each outage event is determined, the compound probabilities are calculated. Compound probability is the probability of joint occurrence of 2 or more events. The compound probability of outage events is used to evaluate the percentage of outage occurrences accounted for by each compound outage event as this is used to determine the autonomy time. Autonomy time is a measure of the time for which the battery would support the load during a mains failure.

The outage duration considered during the design stage of this project is estimated by analyzing the outage statistics data for the test location to determine the shortest outage duration which accounts for the most outage instances, this would ensure the most reliability at the least cost. This estimated outage duration would serve as the basis for the autonomy time when sizing power generation and storage components.

In chapter three, components are sized for the various power supply designs considered in this report, their specifications and costs were tabulated and presented in chapter four. Based on the analysis of the strengths and weaknesses of the various power supply designs, the following recommendations are made.

5.1 Recommendations.

As seen in this report the UPS power supply system offers low cost but is unreliable during extended power outages, for this reason it is recommended for use when outages are expected to be short (0 – 150mins) as it offers low cost and reliability within this range of outage durations. The autonomous solar PV system offers more battery run-time and is designed to be self-sufficient, for this reason the autonomous solar PV power supply is recommended for use in areas which are distant from electrical distribution networks, as they are designed to power the load independently.

The proposed power supply design provides the versatility of having two power sources. The proposed power supply is designed such that it can withstand extended power outages which occur during day-light hours therefore, this design offers more reliability than the UPS and lower cost than the autonomous solar PV system. The proposed power supply design is recommended for use when outage durations are expected to be (0 -150mins) or extended outages are expected during day –light hours (8am – 4pm).

Recommendations for further study: Further studies can be carried out on the following areas:-

1) Protection system designs suitable for the proposed power supply.
2) The viability of alternative power sources such as fuel cell technology.
3) Techniques which can be employed to mitigate the effects of environmental temperature on battery performance.

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