Monitored Performance Data from a Hybrid RAPS System and the Determination of Control Set Points for Simulation Studies

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Abstract:

This paper presents the monitored results from a hybrid Remote Area Power Supply (RAPS) system located in the north-west region of Western Australia. The system under study comprises PV array, a diesel generator, a battery bank and an inverter. One of the major aims of the study is to derive the control set points required for input to simulation studies; as a case study the main control set points for battery, diesel generator, and inverter models of the RAPSIM simulation package are derived. Two separate sets of system control parameters are determined. The first set is based on design data while the second set is derived from the actual measured system performance in the field. The difficulties encountered in obtaining these control set points are discussed in detail and their effect on the results from the simulation program are shown.

1. INTRODUCTION

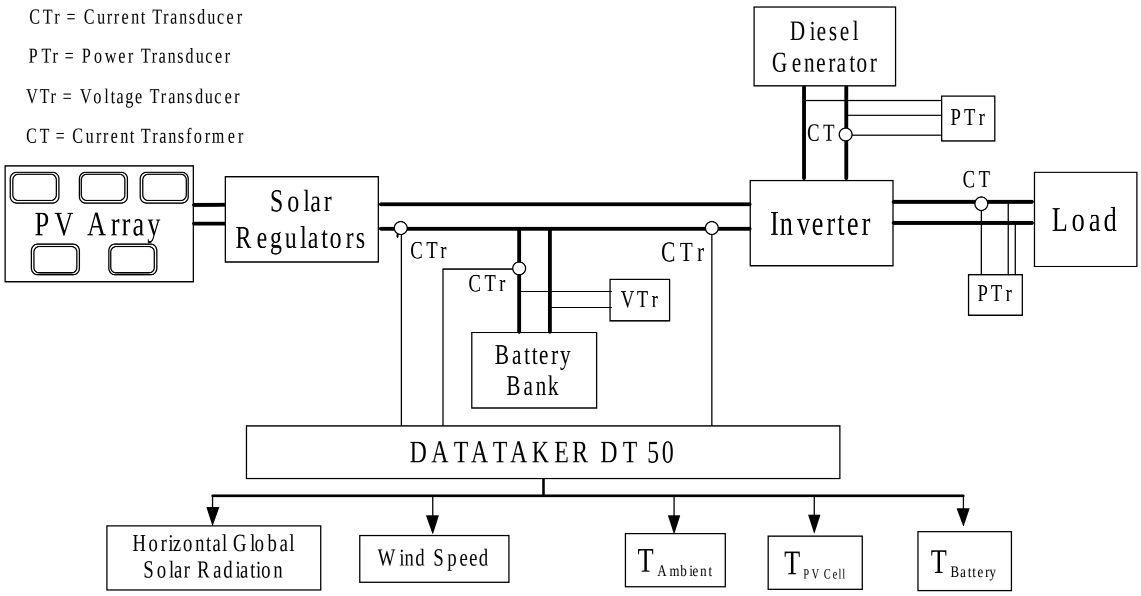
Reliable long-term monitored performance data for a hybrid Remote Area Power Supply system is relatively rare. This study provides the detailed performance data for a switch configured hybrid RAPS system. The monitoring system set up is described with a block diagram showing various monitoring points for the electrical parameters. The accuracy with which the parameters are measured is also presented. This system was designed to supply an average daily load of 74 kWh using photovoltaic modules, battery bank and inverter, with the existing diesel generator operating well loaded for a few hours per day. The monitored data presented covers a period of twenty months from September 1999 to April 2001, and monitoring is still continuing. Such data can be utilized to validate hybrid power system simulation packages. For this task the characteristics of the system components and the control set points are required. The first of these requirements is generally available from manufacturer's specifications while the latter are often propriety information and difficult to determine.

2. THE HYBRID RAPS SYSTEM

The monitoring site is a remote pastoral station located in the Pilbara region in the north-west of Western Australia. The station supports about 12,000 head of cattle. The number of people living on the station varies seasonally and ranges from three to twenty. The RAPS system meets the energy demands of the homestead, the workshop and the surrounding buildings (Fletcher, 1999) and has a switched configuration. In the switch configured hybrid power system the load is supplied either by the inverter or by the diesel generator but not by both simultaneously. One of the drawbacks of this type of configuration is that the diesel generator size should be large enough to meet the peak load without any contribution from the inverter (Nayar et al, 1993). A schematic diagram of the system is shown in figure 1.
The specifications of the various components used in the system are as follows:

- Sixty Photovoltaic modules (each rated at 80 Watts). The PV modules are mounted on five - single axis vertical trackers tracking from east to west. The module tilt angle is just greater than the site latitude.
- A single phase, 19-kVA diesel generator.
- Thirty 4V flooded lead-acid batteries (C100 capacity of 1025 Ah, C10 capacity of 775 Ah).
- A 10 kW (12 kVA) sine wave bi-directional single-phase inverter having an input dc voltage of 120 volts and an output voltage of 240 ac Volts.
- Three AERL 1800 BHV solar regulators.

Fig-1. A block diagram of hybrid RAPS system showing the monitoring points for the electrical parameters



2.1. The Monitoring System

The monitoring system installed at the station was designed according to the International Standard IEC 61724 (IEC, 1998). The Datataker DT50 data logger was used to log ten-minute records of the maximum, minimum, and average values of various system parameters. The following parameters were monitored.

Electrical Parameters	Meteorological Parameters
Battery d.c. Voltage	Horizontal Global Solar Radiation
Battery d.c. Current	PV module Temperature
PV array d.c. Current	Ambient Temperature
Inverter d.c. Current	Battery Temperature
Diesel Generator a.c. Power	Wind Speed
Load a.c Power	

Each parameter is scanned every second and averaged over a period of 10-minutes. From these measured parameters the datalogger computes the PV power, the inverter power, and the battery power. Due to the memory constraints of the PCMCIA card used for data transfer between the site and MUERI, only the ten-minute average values are logged for the meteorological parameters. The accuracy with which various parameters are measured is shown in Table 1 (Fletcher, 1999).

Table 1 The Accuracy of Various Monitoring Parameters

Parameter	Solar Radiation	PV Power	Battery & Inverter Power	Generator & Load power	PV Current	Battery & Inverter Current	Tempe-rature	Battery Voltage
Accuracy	±3.15%	±3.0%	±2.8%	±1.55%	±1.35%	±1.15%	±2.95%	±1.65%

3. MONITORED DATA DISCUSSION

The monitored data indicates that the system has performed extremely well over the twenty month period for which data is available. The monthly average daily values for various monitored and calculated parameters are shown in Table 2. In this twenty month period, the system was shutdown for only thirteen days. Analysis of the monitored data and comments received from the monitoring site were used to ascertain the reasons for any system malfunctions. The inverter faults caused the loss of a few days of data during October 1999 and September 2000. The cyclone John caused the loss of a couple of days of data in December 1999. The data points when the system was shutdown (invalid data) are flagged for future reference and ignored in this analysis. The solar radiation values shown in table-2 represent the global hemispherical solar radiation measured by a photoelectric pyranometer on the horizontal plane. Over the twenty-month monitoring period, 97.6% of the collected data was valid. The average daily load was 77.8 kWh, and the peak 10-minute average load was 14.8 kW, while the peak hourly average load was 13.1 kW. During the summer months, December to February, the prolonged use of air-conditioners, freezers and refrigerators correlates with the high load demand. In Jul 2000 the extended use of the washing machine and welding machine, and in Sep 2000, the presence of more people at the station, correlates well with the high load for these periods.

The average daily values for the horizontal solar radiation indicate that this site enjoys a good solar resource. The lower PV output during Dec-99 was due to some damage to the PV array trackers during a cyclone which caused the PV array to be locked in one position for a couple of weeks. In Dec-99 the peak diesel generator loading dropped to 70% of its rated output. This was attributed to a problem with the diesel generator governor. When this problem was fixed in Oct-00 the peak diesel generator loading returned to a value very close to its original value. The PV contribution to the system output for each month is calculated as the ratio of the average daily values of the PV output to the sum of the PV output and the diesel generator output. The PV array contribution to the system output is 34.5%, which indicates that the renewable component covers quite a good proportion of load. It is also evident from the data that on normal sunny days during the daytime the PV array produces enough energy to meet the system load and also to charge the batteries for several hours. The lower PV array output during some of the months is probably due to the lower solar radiation levels and/or the higher ambient temperatures. Also the solar regulators control the PV array output depending upon the battery voltage, which in turn is related to the system load.

Table-2 The Average System Performance Parameters

Month	Load (kWh/day)	Diesel generator output (kWh/day)	Diesel generator operating hours/day	Diesel generator number of starts/day	Horizontal global solar radiation (kWh/m2/ day)	PV array output (kWh/day)	PV array contribution to system output (%)	Battery energy in (kWh/day)	Battery energy out (kWh/day)	Max_bat_ char_rate (kW)	Max_bat_ disch_rate (kW)	Percentage of valid data
Sep-99	71.8	45.6	3.6	1.8	6.1	34.9	43.3	26.0	24.4	12.2	7.8	99.72
Oct-99	66.7	40.7	3.3	1.6	6.7	35.2	46.3	25.1	22.5	12.0	6.4	95.92
Nov-99	78.2	52.8	4.1	1.7	7.3	35.6	40.3	30.3	27.9	11.7	6.1	99.84
Dec-99	74.8	60.5	5.5	1.8	6.7	26.6	30.5	37.0	32.6	11.6	6.6	97.42
Jan-00	84.1	66.5	6.6	1.9	6.7	30.2	31.3	36.4	32.5	10.8	8.0	99.88
Feb-00	82.8	67.0	6.6	1.3	6.1	28.2	29.6	35.9	32.4	9.2	5.7	99.88
Mar-00	74.0	61.4	6.2	1.4	5.2	24.9	28.9	35.8	31.9	9.5	8.3	99.95
Apr-00	77.7	57.4	6.0	1.2	5.2	29.3	33.8	29.4	27.4	8.8	9.0	100.00
May-00	64.3	43.9	4.9	1.3	4.4	28.8	39.6	25.0	22.3	10.0	7.6	99.88
Jun-00	66.2	44.8	4.9	1.5	4.3	29.5	39.7	23.7	21.4	9.9	12.7	99.88
Jul-00	86.7	67.5	7.5	1.8	4.2	29.1	30.1	29.6	26.3	9.7	8.4	99.80
Aug-00	75.5	52.6	6.0	2.0	5.0	32.4	38.1	27.3	24.0	9.6	8.0	99.66
Sep-00	86.5	66.4	7.1	1.8	5.3	31.3	32.0	30.9	27.4	9.5	7.0	85.60
Oct-00	73.0	50.0	6.0	1.5	6.1	31.8	38.9	28.6	23.2	12.1	8.5	88.60
Nov-00	80.5	60.2	5.2	1.8	6.9	34.1	36.2	34.9	29.2	11.6	6.9	99.84
Dec-00	91.0	79.8	6.2	2.0	6.6	29.8	27.2	46.7	38.9	11.7	6.0	99.84
Jan-01	92.9	85.5	6.6	1.8	6.0	26.4	23.6	47.9	39.3	11.6	5.5	99.90
Feb-01	81.1	70.5	5.9	1.4	6.0	27.6	28.1	41.9	34.5	11.5	6.8	99.89
Mar-01	75.0	56.1	4.9	1.1	6.2	32.8	36.9	34.1	28.4	11.4	6.8	86.20
Apr-01	73.1	56.4	4.7	1.2	5.3	30.8	35.3	33.7	27.6	11.4	6.5	100.0
Average	***77.8***	***59.3***	***5.6***	***1.6***	***5.8***	***30.5***	***34.5***	***33.0***	***28.8***	***10.8***	***7.4***	***97.59***

4. CONTROL PARAMETERS FOR RAPSIM SIMULATION

The monitored data provides very valuable data for validation of simulation packages. These simulation packages utilize time series of weather and load data together with system component models to predict the performance of hybrid RAPS systems. Built into these simulation programs are the models for system control and one of the difficulties in using these programs is determining the combination of system control parameters which best models the real system operation. In this study the determination of these control parameters for the RAPSIM simulation program (RAPSIM User's Guide, 1997) is used to highlight these issues. RAPSIM is a Windows based software package that can simulate the performance of a range of hybrid power systems. The main inputs required by RAPSIM are time series of horizontal global solar radiation, wind speed, ambient temperature and system load. The system components need to be specified in terms of their size and performance and this information is generally obtained from manufacturer's specification sheets. Several key system control parameters also need to be supplied to the program.

The main control parameters and set points required by the RAPSIM program are:

- The maximum and minimum battery state of charge (SOC) set points - these determine how much of the available battery capacity will be utilized by the system

- The inverter loading (fraction of rated inverter output) value that triggers a diesel generator start and the transfer of load from the inverter to the diesel generator
- The maximum battery charge and discharge rates
- The optimum and minimum diesel generator loading values

Table 3 shows the control parameters selected for two simulation runs: Run0 and Run1. The control parameters for Run0 are derived from general information available on the particular system being considered together with general rules of thumb for such systems. It is the type of control set point data that a designer would choose when investigating the feasibility of such a system.

The control parameters for Run1 are selected based on the analysis of monitored data and the information provided by the system designer, suppliers and the manufacturers of the system components. It is not straightforward to determine the exact control parameters set in the system, as some of the detailed information about the control settings is propriety information and so not available. The complexity of the power flows in the system and the fact that the data available is in the form of 10-minute average, minimum and maximum values of various parameters complicates the task because the precise values triggering some system changes are absorbed within the ten minute values.

Table 3 RAPSIM Simulation Control Parameters for Run0 and Run1

PARAMETER	Run 0	Run 1
Low battery SOC control point	0.50	0.52
High battery SOC control point	0.90	0.80
Optimum diesel generator loading (Fraction of rated power)	1.0	0.7*
Diesel generator start at fraction of rated inverter output (%)	0.7	
Maximum battery discharge rate (kW)	10	9
Maximum battery charge rate (kW)	12	12
Diesel generator maximum loading (Fraction of rated output)	1.0	1.0
Diesel generator minimum loading (Fraction of rated output)	0.4	0.4
Battery capacity available after recharge (Ah)	920	967
Hybrid system inverter configuration	Switched	
Maximise diesel generator efficiency	Selected	

* The diesel generator optimum loading value of 0.7 is chosen for the period Jan-Oct 2000, while for the period Nov-Dec 2000 a value 1 is chosen.

4.1. Battery Control Points:

The battery model in RAPSIM is based on an SOC counter and the system changes are triggered by SOC set points. In reality, the system changes are triggered by voltage set points and so there is the challenge of relating SOC set points to battery voltage set points. For the Run 0 case, it was assumed that the battery was discharge to 50% SOC, a standard design assumption, while an upper limit of 90% was chosen in recognition of the fact that the battery would seldom be fully charged. The battery capacity was assumed to be the C-50 value.

When the diesel generator starts due to the low battery voltage the monitored data indicates that the 10-minute average battery voltage value is around 117 volts. This agrees with information supplied by the system designer that the low battery cut off voltage value is set to 117.5 volts, and it is temperature compensated. However, RAPSIM required an SOC value corresponding to this condition. For the Run 1 data set, this lower battery SOC control point value was obtained using the following method. The net current discharge from the battery over a cycle (the period from when the diesel generator stops until the time of the next diesel generator start) can be calculated by integrating the current entering and leaving with the battery (considering the current taken from battery as positive and current entering into the battery as negative) over that cycle. A charging efficiency factor η_C is introduced to account for the columbic efficiency of the battery. At the end of cycle (i.e. when the diesel generator starts) the battery SOC can be calculated using following equation [a] (Perhia, 1998),

$$\text{Battery SOC} = SOC_{Max} - \{[\, I_D{*}T_D - (I_C{*}T_C){*}\,\eta_C\,] / C_{BAT}\} \quad \_\_\_\_\_\_[a]$$

Where I_D is the battery discharge current in Amperes, T_D is the discharge interval in hours, I_C is the battery charge current in Amperes, T_C is the charge interval in hours, and C_{BAT} is the battery capacity in Ah. The charging efficiency factor η_C is assumed as 80%.

When the battery is discharged at a current and temperature other than the standard C Ratings, the battery discharge capacity can be computed from the following equation [b] (Copetti et al, 1993),

$$C = 1.1 * C_{100} [\{ 1 + 0.005 (T - T_{ref})\} / \{1 + 0.1 * ([I / I_{100}]^{\wedge}0.9) \}] \qquad [b]$$

In the above equation, T is the battery temperature in °C, T_{ref} is the reference temperature (25°C), I is the battery discharge current, and C_{100} and I_{100} are the battery capacity and the battery discharge current at the standard C100 discharge rate. By selecting cycles from the monitored data which were most likely to have been terminated by a diesel generator start triggered by a low battery voltage, the above equation was used to estimate the available battery discharge capacity. These cycles selected generally occurred on days with relatively high loads when the battery and inverter were able to meet these loads without diesel generator backup. Such cycles were quite rare in the monitored data set. The resulting value for battery capacity was 967 Ah.

The other parameter needed to use equation [a] is SOC_{Max}. At the time of battery charge termination (when the diesel generator turns off) the battery voltage was observed to be around 2.45 V/cell. According to the battery manufacturer the batteries reach a fully charged state at around 2.6 V/cell (Installation & Maintenance manual, Enersun). Based on this, and the standard discharge curve supplied by the battery manufacturer, the value of the high battery SOC control point, SOC_{Max} was estimated to be 0.90. By applying equation [a] to a few of the cycles described above, the lower battery SOC control point (SOC at the end of discharge period) was estimated as 0.62. In RAPSIM the battery model assumes taper charging once the battery exceeds an SOC value of 0.8, but in the monitored data no taper charging was observed. To achieve a similar charging regime the SOC control point range for the RAPSIM simulations was shifted from 0.62-0.90 to 0.52-0.8. It is worth noting that this change does not affect any of the battery model calculations except for the battery life.

In the monitored data the maximum battery charge rate ranges from 9 to 12 kW while the maximum battery discharge rate ranges from 6 to 9 kW. During the off peak period when the diesel generator was not operating, the maximum load requirement was around 7kW. By selecting the maximum discharge rate of 9 kW the battery bank can easily meet this load without any diesel generator and PV contribution. Occasionally during the daytime when the PV power was available the diesel generator still operated to meet the load. In those instances, to ensure maximum utilization of the available PV array output and to ensure that the diesel generator can operate at an acceptable loading, a maximum battery charge rate of 12 kW is selected for the Run1 case. Similar values are chosen for the Run0 scenario as they represent the expected maximum power draw by the inverter in the case of battery discharge, while an allowance for additional PV charging is made in determining the maximum battery charging rate.

4.2. Inverter Control Points

For the Run0 values, a fairly standard value of 0.7 is chosen for the inverter load that would trigger a diesel generator start. Such a value means that the battery storage is well utilized and also there is still capacity for significant load increase in the period when the diesel generator is starting up and coming on line.

For the Run1 values, analysis of the monitored data indicated that the diesel generator starts triggered by high load on the inverter occur when the load on the inverter: is high,

- Is high for very short periods; excluding the surge loads when an equipment drawing high power is starting up (eg. 11 kW for 30 to 40 seconds), or
- Is high for a longer period (and so can be met more efficiently by the diesel generator eg. 8 kW load for a couple of minutes and 5 kW load for 20 to 25 minutes).

This observation correlates with the information provided by the inverter manufacturer that the inverter control algorithm triggers a diesel generator start after 30 seconds, 2 minutes, 10 minutes or 30 minutes depending upon the magnitude of the load and the battery voltage (Brown J, 2001). The diesel generator starts when the load on the inverter reaches one of its set points. To estimate the exact inverter loading when the diesel generator starts is complicated, as the precise value is lost in the averaging of results over the 10-minute period of the monitored data. To determine an appropriate value for the set point in the simulation program is difficult because the model in the program is simpler than the multiple start algorithm in the real inverter control system, and because the simulation program uses hourly time steps while it is short term loading that generally start the diesel generator. In the end an hourly inverter loading value of 0.7 was selected to trigger a diesel generator start.

4.3. Diesel Generator Control Points

The existing 32 kVA, 3-phase diesel generator was used in the monitored system. At the time of system installation it was converted to a single-phase unit of 19-kVA output (or 15 kW output at an average power factor of 0.8). For the Run0 data set an optimum diesel generator loading value of 1 was chosen to reflect a good generator that operates well at full load. For the Run1 data set, monitored data indicated that the diesel generator was initially capable of providing at least 15 kW. Therefore the maximum diesel generator loading value was set to 1.0. However, for a block of time during the monitoring period problems arose with the governor of the diesel generator. The monitored data indicated that the peak hourly loading on the diesel generator dropped dramatically from 15 kW (or 19 kVA) to 10 kW (or 13 kVA). For the period during which this condition lasted, a diesel generator optimum loading value of 0.7 was selected to reflect this loss of capacity of the diesel generator.

Diesel generators need to be prevented from operating at very low loading as such operation will lead to incomplete combustion and glazing of the cylinder walls. This will increase the maintenance requirements for the diesel engine considerably. Therefore a low load limit is generally specified in the hybrid systems comprising a diesel generator. For the Run0 case the standard rule of thumb of 40% of diesel generator capacity was used. Inspection of the monitored data indicated that the lowest hourly average loads experienced by the diesel generator were around the 6 kW level. Assuming a full load capacity of 15 kW, this leads to a value of 40% for the minimum diesel generator loading in the Run1 data set. In this case the result is the same as that for Run0. The RAPSIM program also allows for a choice of maximizing either diesel generator efficiency or renewable energy utilization and in this instance the maximizing the diesel generator efficiency option seemed to best match the observed system operation.

5. SIMULATION RESULTS FOR RUN0 AND RUN1

Table 4 shows a comparison between RAPSIM simulated performance parameters obtained with the Run 0 and Run 1 control set points. There are some significant differences between these two sets of results, notably in the average daily fuel use and the average diesel generator operating hours per day. Although it is not a focus of this paper, it is interesting to note that the results of Run 1 are closer to the monitored data. These differences clearly indicate how critical the selection of control parameters is in using simulation packages to predict system performance.

Table 4 RAPSIM Simulation Results for Run0 and Run1

Year 2000	Run 0	Run1
Diesel generator output (kWh/day)	64.9	63.2
System fuel efficiency (kWh/Litres)	3.71	3.38
Diesel generator fuel use (Litres/day)	21.2	23.2
Diesel generator operating hours / day	5.32	6.06
Number of diesel generator start / day	0.96	1.14
PV array output (kWh/day)	30.0	30.1
Battery energy in (kWh/day)	42.1	38.6
Battery energy out (kWh/day)	34.0	30.7

6. CONCLUSIONS

Since the installation of the monitoring set-up, the system has performed well. The renewable contribution to the system output is 34.5%. This study shows that a well-designed hybrid power system can be a reliable and satisfactory power supply for remote area applications. In terms of determining the control set points for use in simulation studies, the paper has indicated the difficult issues that arise in such a task. Significant differences were observed in the results of a simulation program, RAPSIM, when control set points were based on the monitored data, rather than values generally used in the system design. These differences in the key performance parameters clearly indicate how critical the selection of control parameters is in using simulation packages to predict system performance. The next step in this work is to investigate whether refining some of the RAPSIM control set points derived in this study can achieve a closer match between the predicted system performance and the monitored performance. The effects of the sensitivities of system components specifications and the system control parameters on the overall system performance will also be investigated.

7. ACKNOWLEDGMENTS

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