OPTIMISATION OF A HYBRID ENERGY SYSTEM USING SIMULATED ANNEALING TECHNIQUE

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ABSTRACT

This paper reports an optimisation algorithm based upon the simulated annealing technique for a hybrid energy system. The hybrid energy system is an integrated diesel-generator/battery-inverter system developed for remote communities where the supply of the main electrical power is unavailable. The developed algorithm provides optimal generator setting and battery charge/discharge schedules for a given daily load cycle. It has been applied to a test example and the simulation results are presented.

INTRODUCTION

In areas where the connection to the main electrical power grid is uneconomical, stand-alone diesel generators are usually used to meet the demands of electrical energy. Typical examples are the remote communities and homesteads in the Australian outback. Depending on the size of such communities, power consumption may vary from 25 kWh up to 300 kWh per day. Due to the prolonged operating periods and the irregularities in the daily load characteristics, these systems are usually operated inefficiently resulting in high running and maintenance costs.

By integrating a battery bank and a power conditioner, a diesel-battery-inverter hybrid system has been developed in Western Australia [1,2]. In this arrangement, the battery is used to store the extra energy from the generator when the demand is low, and to supplement the power supply when the load demand is high. This arrangement increases the efficiency and the maximum output capability of the system.

Currently, the control of the system operation is based on the existing battery state-of-charge and present load demand [3]. The control algorithm aims at operating the generator within its most efficient region and keeping the battery fully charged. However, as the subsequent load demands have not been taken into consideration, setting the generator at the most efficient level may not result in the lowest overall operating cost.

This paper reports an optimisation algorithm based upon the simulated annealing (SA) technique for the scheduling of the generator settings and the battery charge/discharge schedule. This will improve the hybrid energy system performance and reduces the overall running cost. Problem formulation, development of the optimisation algorithm and simulation results are described in the following sections.

HYBRID ENERGY SYSTEM

The schematic diagram of a parallel Hybrid energy system is shown in Figure 1. The system consists of a diesel generator, a sinewave inverter and a controller unit [1,2]. The construction of the inverter is based upon power MOSFET technology and pulse-width-modulation technique. The quality of the waveform output is comparable to that delivered from the main power grids. The inverter can also be operated in reverse mode and acts as a battery charger. To meet the load demands, the controller operates the diesel generator and the inverter in one of the following modes:

(a)	mode 1:	Inverter only
(b)	mode 2:	Both diesel and inverter in parallel supplying load
(c)	mode 3:	Diesel and inverter in parallel with inverter in reverse as a battery charger

At present, the setting of the diesel generator is based upon fixed settings at different percentage of the system load and the state of charge of the battery. An example of such strategy has been reported in reference 3.

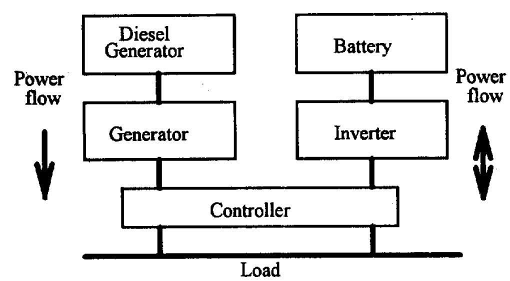

Figure 1: A parallel hybrid-energy system

PROBLEM FORMULATION

1. Load Profile

Given a daily load profile as shown in Figure 2, it can be discretised as a load vector PL, $[PL_0, PL_1, ...PL_i, ...PL_I]$, where I is the number of intervals and the duration of each interval is denoted as p.

2. Load-Balance Equations

When the system losses are neglected, the generator and the inverter/battery operate under one of the three modes described previously and at time interval i, the load balance equations are:

(a) mode 1: $PL_i = PB_id$ kW (1)
(b) mode 2: $PL_i = GP_i + PB_id$ kW (2)
(c) mode 3: $PL_i + PB_ic = GP_i$ kW (3)

where PB_id is the power delivered from the battery/inverter,
PB_ic is the power from the diesel generator used to charge the battery, and
GP_i is the setting of the generator.

3. Battery/Inverter

A linear model with negligible leakage is used for the lead-acid type storage battery. The state of charge or stored energy of the battery can be calculated from the following equations.

(a) Battery discharging :
$$EB_i = EB_{i-1} - (PB_id * p) / \eta d \quad \text{kWh} \quad (4)$$
(b) Battery charging :
$$EB_i = EB_{i-1} + (PB_ic * p) * \eta c \quad \text{kWh} \quad (5)$$

where EB_{i-1} and EB_i are the battery energy at the beginning and the end of interval i respectiveiy, and
ηd and ηc are the battery discharging and charging efficiencies respectively.

Although it is theoretically possible to fully discharge the battery, it is not recommended in practice. Hence, it should be ensured that a minimum amount of charges is retained. This can be expressed as the constraints,

$$EBmin \leq EB_i \leq EBmax \quad \text{kWh} \quad (6)$$

To minimise the running time of the generator during the night, the battery should be re-charged to as high as possible at the end of the 24 hour period. This will enable mode 1 to be executed during the low demand intervals and the operating hours will be reduced.

4. Diesel Generator

Figure 3 shows a normalised specific fuel consumption characteristic for a plant in the size of 20-30 kVA. The data shown is normalised to unity at 3 kWh/litre. The fuel consumption function, f, can be modelled by a polynomial expression or piecewise quadratic function. At any instance i, the rate of fuel being burnt by the generator at power level Pi kW, Fi is expressed as

$$F_i = f(GP_i) \quad \text{litres/hour} \quad (7)$$

The operating range of the generator is also limited to the following constraints.

$$Pmin \leq GP_i \leq Pmax \quad \text{kW} \quad (8)$$

Within 24 hour, the total fuel consumed can be calculated from

$$FT = \sum_{i=1}^{I} F_i * p \quad \text{litres} \quad (9)$$

Given a fuel price of K \$/litre, the total fuel cost, FC is calculated as follows.

$$FC = K * FT \quad \text{\$/day} \quad (10)$$

Taking in account the routine maintenance and major overhaul costs, the total operational cost can be derived.

$$TC = \{ FC + \sum_{i=1}^{I} M_i * p\} \quad \text{\$/day} \quad (11)$$

where M_i is the maintenance cost expressed in \$/h.

5. Optimisation Objective

The objective of the optimisation algorithm is to find the solution vectors of the generator setting schedule, GP, $[GP_0, GP_1, ... GP_i, ... GP_I]$ and the battery schedule, PB $[PB_0, PB_1, ... PB_i, ... PB_I]$ which minimise the total cost TC in equation (11) while satisfying the load balance equations (1-3) and the operation constraints described in sections 3 and 4.

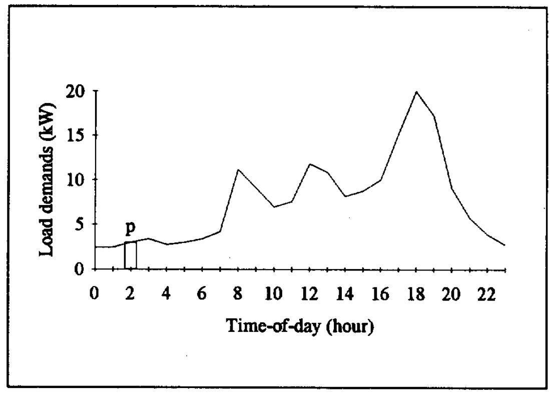

Figure 2: Typical daily load profile

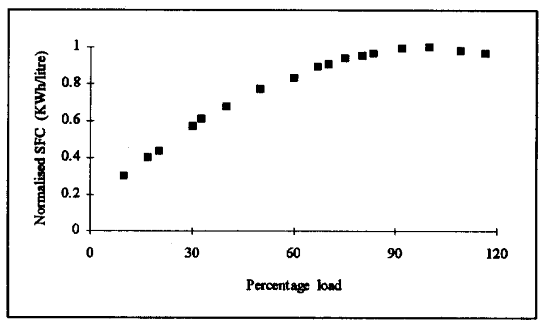

Figure 3: Diesel generator specific fuel consumption characteristic

SA-BASED ALGORITHM

The SA technique was first applied to solve combinatorial optimisation problem by Kirkpatrick et. al. [4]. It has also been applied to solve various power system engineering problems such as optimal network tearing [5], unit commitment [6] and maintenance scheduling [7]. Although the technique is essentially a random search method similar to the iterative improvement algorithm, it may accept an inferior solution based upon a probabilistic measure. The algorithm is therefore possible to escape from being trapped within local minimum points and to seek after the global or near global solution in the overall solution space. In addition, the algorithm is independent from the initial starting condition. Unlike conventional approaches such as the Lagrange method, it is not restricted by the system function and the system operation constraints. In contrast to the dynamic programming method, the computer memory requirement is minimal.

1. The Annealing Process

Annealing is the physical process of applying heat to a solid until it melts. The melted solid is then allowed to cool slowly in a controlled manner. During the course, the free energy of the solid will have to be minimised and when the temperature is low enough, the solid will crystallise into a perfect lattice.

2. Application to Optimisation Problems

In applying the SA technique to solve the combinatorial optimisation problems, the basic steps can be summarised in the flow chart shown in Figure 4.

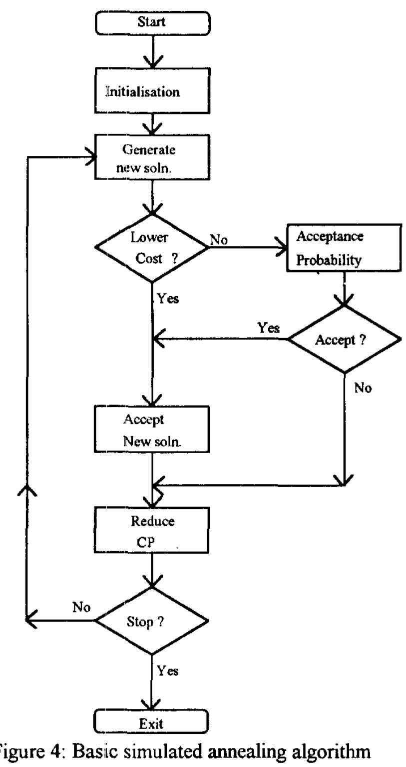

Figure 4: Basic simulated annealing algorithm

The main difference of the SA algorithm as compared to the iterative improvement algorithm is the inclusion of the acceptance probability, Pa which is defined as

$$Pa = \exp(\delta E/CP) \quad (12)$$

where δE is the difference in the objective cost, and
CP is the control parameter.

It is the introduction of this probabilistic factor which allows an inferior solution to be accepted. The control parameter, CP within the expression (12) is analogous to the temperature in the physical annealing process. When the value of CP is high, the chances of accepting a poorer solution is also high. This enables the solution process to 'jump' out of the local minimum points. The reduction of the CP value can be compared to the cooling process. As CP gets low, the solution will settle into the global or near-global optimal point. Hence, the term 'simulated annealing' is used for this optimisation technique.

3. Application to the Hybrid Energy System

On the basis of the flow chart illustrated in Figure 4, the Hybrid Energy system optimisation algorithm is described as follows.

A. Starting from an initial generator and battery schedule.
B. Calculate the total cost, TC associated with this solution.
C. Generate new generator and battery schedules by perturbing the current schedules while satisfying all the constraints.
D. Calculate the new cost associated with the new schedules.
E. New schedules are only accepted according to the following criteria:

  (a) if new cost is lower.
  (b) if new cost is higher, and the acceptance probability, Pa is higher than a randomly generated number, R, between 0 and 1.

F. Steps C to E are repeated for a specific number of trials and then the control parameter is reduced at a predefined rate.
G. Steps C to F are repeated for a fixed number of iterations.

APPLICATION EXAMPLE

The algorithm has been developed and implemented in C++ programming language. The software program runs on a PC-486/33MHz microcomputer. The discretised load profile of a typical medium size community is listed in Table 1. The value of I and p are taken to be 24 and 1 hour respectively. The total consumption within the 24-hour period is 183 kWh.

Table 1 : Example Load Profile

Hr	00	01	02	03	04	05	06	07
kW	2.44	2.42	3.00	3.40	2.72	3.00	3.40	4.20

Hr	08	09	10	11	12	13	14	15
kW	11.20	9.10	6.96	7.58	11.82	10.88	8.18	8.78

Hr	16	17	18	19	20	21	22	23
kW	10.00	15.15	20.00	17.28	9.10	5.76	3.94	2.72

Data from the diesel generator specific fuel consumption characteristics have been used and a piecewise quadratic function provides the best fit. The coefficients are listed in Table 2 below.

Table 2: Diesel Generator Characteristic

	Coefficients		
Range (kW)	a	b	c
1.4 - 8.4	-0.0113	0.3527	1.1531
8.4 - 16.3	0.0188	-0.1816	3.5551

$$F = \{a(P)^2 + b(P) + c\} \text{ litres/hour}$$

The capacity of the battery used in the example is 52 kWh and a minimum of 50% of the charge is expected to be retained. The efficiencies ηd and ηc are both assigned with a value of 86%. The maintenance cost of the system is based upon the major overhaul and routine maintenance costs. The former costs $8,000 for every 20,000 running hours, whereas the latter averages $100 per 500 operating hours. This gives a figure of $0.60/hour. Finally, the fuel price, K, is based upon $0.68 per litre.

With respect to parameters within the SA algorithm, the initial control parameter, CP is assigned with a value of 1000 and 100 iterations have been permitted. Within each iteration, 1000 trials are executed and the reduction ratio of the control parameter is 0.95. At the end of the cycle, the algorithm is expected to charge the battery to at least 90% of the full capacity.

The algorithm has been applied to two cases of initial battery conditions, (a) fully charged and (b) 90% charged. The solution schedules are tabulated in Table 3 below.

Table 3 : Solution schedules of test example

0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11.976	9.403	11.061	11.755	10.684	10.201	11.402	11.169
11.493	14.000	14.000	14.000	11.809	9.206	11.993	16.300
(i) Generator Schedule							
2.837	2.814	3.488	3.954	3.163	3.488	3.954	4.884
-0.667	-0.260	-3.527	-3.591	1.321	0.790	-2.771	-2.055
-1.284	1.337	6.977	3.814	-2.330	-2.963	-6.925	-11.679
(ii) Battery charge/discharge Schedule, +ve discharge, -ve charge							
49.163	46.349	42.861	38.907	35.744	32.256	28.302	23.419
24.086	24.346	27.873	31.463	30.142	29.352	32.123	34.177
35.461	34.124	27.147	23.333	25.663	28.626	35.552	47.230
(iii) State-of-charge within Battery							

(a) full initial charge

0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.921
11.847	11.320	11.115	10.798	11.841	10.848	11.334	11.147
10.664	14.000	14.000	14.000	12.130	11.183	9.721	10.758
(i) Generator Schedule							
2.837	2.814	3.488	3.954	3.163	3.488	3.954	-6.640
-0.557	-1.909	-3.573	-2.768	-0.018	0.037	-2.712	-2.036
-0.571	1.337	6.977	3.814	-2.606	-4.664	-4.971	-8.038
(ii) Battery charge/discharge Schedule, +ve discharge, -ve charge							
43.963	41.149	37.661	33.707	30.544	27.056	23.102	29.743
30.299	32.209	35.782	38.549	38.568	38.530	41.243	43.278
43.849	42.512	35.535	31.721	34.326	38.990	43.962	52.000
(iii) State-of-charge within Battery							

(b) 90% initial charge

In the first case, the total running cost obtained is $54 for the 24 hour period and the final state of charge of the battery is 47 kWh. The generator remains off for the first 8 hours and it operates at its most efficient point during the peak load intervals. At the final interval, the generator is set at maximum so as to ensure the battery is charged to as high as possible before the generator is turned off. In the second case, the total operating cost is found to be $56 for the same period. It is observed that the battery is fully charged at the end of the cycle. Due to a lower initial state of charge, the generator is turned on one hour earlier. Regarding the peak load and final intervals, similar settings of the generator are obtained. In addition, the battery is not overcharged and no energy is wasted. The average computing time for both cases is 300 seconds.

As compared to a stand-alone diesel generator, a higher capacity unit is required to meet the peak load demands and the generator has to be run continuously. The study in reference 3 reported that the average fuel cost for a large diesel unit to meet a 150 kWh daily demand is $86. This illustrates a considerable saving on the running cost is achieved by the hybrid energy system.

CONCLUSION

An optimisation algorithm for the hybrid energy system has been developed. It is based upon the simulated annealing technique and it is used to find the optimal generator setting and battery charging/discharging schedules. The algorithm is independent of the system characteristics and operating constraints. Under these schedules, performance of the battery is maximised and running cost of the generator is minimised. It can be extended to include a more complex battery model and other renewable sources of energy such as solar and wind power.

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