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COMPARISON OF AC, DC, AND AC/DC BUS CONFIGURATIONS FOR PV HYBRID SYSTEMS

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ABSTRACT

In North America, the various components of a hybrid photovoltaic system are typically interconnected via an AC/DC bus: the photovoltaic array feeds the battery by a DC connection, the engine-driven generator (genset) charges the battery through a rectifier and powers AC loads directly whenever it is operating, and an inverter supplies the AC loads at other times. Other bus configurations have been promoted in recent years, however. In an AC bus configuration, module or string inverters convert the output of the photovoltaic array to AC, a bidirectional converter connects the battery to the AC bus, and a rectifier feeds DC loads. In a DC bus configuration, a variable speed genset having DC output is used, and an inverter meets all AC loads.

In the present study, PVToolbox, a photovoltaic hybrid system simulation package developed at CETC-Varennes, is used to compare these three bus configurations. PVToolbox is first used to recreate, with very good accuracy, the results of a European study favourable to the AC bus (Gabler and Wiemken, 1998). Then the performance of the AC bus and AC/DC bus are compared over a range of conditions. The annual load is kept constant, but the diuranal and seasonal pattern of variation and the size of the array are varied. Finally, the above two bus configurations are compared to the DC bus.

Gabler and Wiemkin's finding that the AC bus and AC/DC bus have comparable performance is contradicted by this study: if maximum power point tracking is included in both systems, the AC bus system requires about 10 to 18% more electrical energy from the genset than does the AC/DC configuration. The DC bus system, on the other hand, is comparable to the AC/DC bus system, requiring at most 2 to 3% more electricity from the genset. The fuel consumption is 10 to 14% lower in the DC bus system, however, but for a variety of reasons, this study probably overstates the gains of the variable speed genset operation.

The conventional AC/DC bus system offers some compelling advantages compared to either AC or DC bus systems. The genset can satisfy AC loads directly, unlike in DC bus systems, and its fuel consumption suffers only during part load operation. If intelligent dispatch strategy can minimize the time spent at part load, the fuel consumption may be even lower than that of the DC bus system.

INTRODUCTION

Photovoltaic (PV) hybrid power systems are used throughout Canada to power small electrical loads in locations where grid electricity is not available or is very expensive. Consisting of a photovoltaic array, fossil-fuel powered genset, battery, and controls and power converters as required, the hybrid system combines the advantages of PV and the genset: the PV provides power with no fuel costs, and the genset guarantees power availability even during extended periods with little sunshine.

The photovoltaic array supplies direct current (DC); the electricity flowing into or out of the battery is also DC. In contrast, most gensets supply alternating current (AC), and loads may be AC, DC or both. There exists, therefore, a variety of possible bus configurations for the system. In an AC bus configuration, as shown in Figure 1, the interface between the various components is AC. The PV array output is converted to AC with an inverter (or number of string or module inverters) and the battery is connected to the other components via a bi-directional converter or paralleled inverter and rectifier. This converter is also responsible for performing charge control. DC loads, if any are connected directly to the battery.

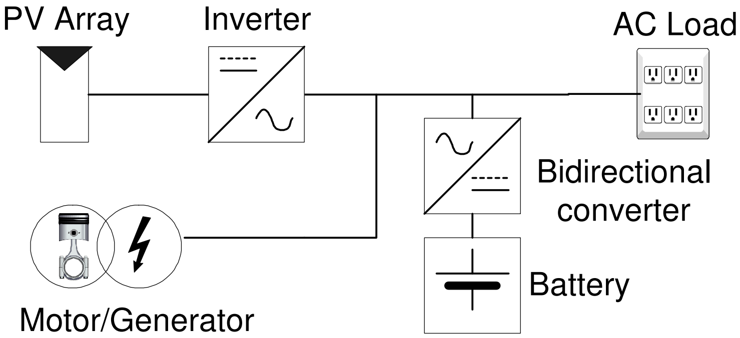

Figure 1: AC Bus Configuration

In a DC bus system (Figure 2), direct current is the common system currency. AC loads are supplied through an inverter. A special genset, producing DC rather than AC, is used.

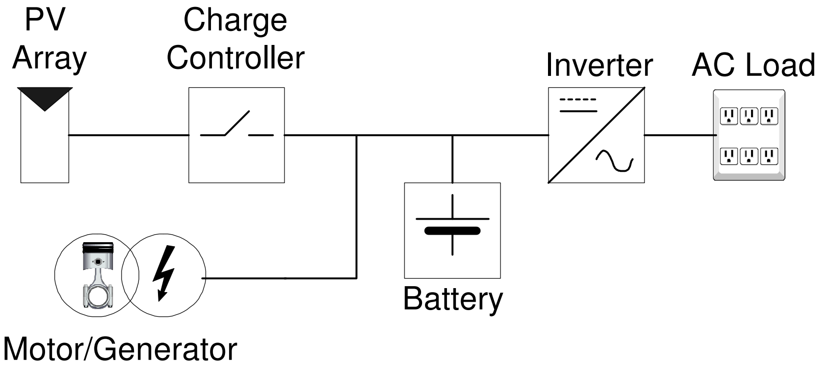

Figure 2: DC Bus Configuration

The AC/DC bus configuration contains a secondary AC bus, to which AC loads are connected, in addition to the principal DC bus (Figure 3). A rectifier transfers power from the AC bus, that is, from the genset, to the DC bus, and an inverter transfers power in the opposite direction, as necessary. This configuration is the one most commonly used for small PV hybrid systems.

Intuitively, the AC/DC bus and the DC bus configurations make more sense than the AC bus. In the AC bus system, all PV output destined for a DC load or the battery suffers the losses associated with both an inverter and a rectifier. Yet the AC bus configuration has its proponents, especially in Europe (Haas et al., 1997). They argue that it is a more modular configuration, facilitating expansion to cope with increasing energy and power needs, the interconnection of components from different manufacturers, and the connection to the conventional grid, where available. In addition, it permits the use of module or string inverters, which may benefit from economies of scale in production not enjoyed by the larger, specialized inverters typically employed in hybrid systems. Furthermore, wiring of the photovoltaic array may be less expensive: the inverters invariably operate at the mains voltage (e.g., 120 V_{AC} in North America), which is higher than the typical small hybrid system DC bus.

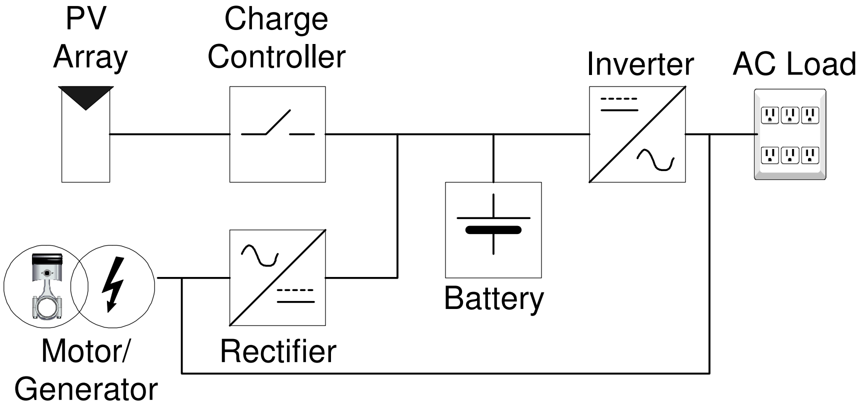

Figure 3: AC/DC Bus Configuration

In a recent study, Gabler and Wiemken (1998) argue that, contrary to intuition, "in spite of the additional transforming processes, the AC coupled system is not far away in performance" from the AC/DC bus system. For metrics of system performance, they emphasize the solar fraction (fraction of end-use energy supplied by the PV system) and performance ratio (the PV-generated energy delivered to the end-use as a fraction of the "nominal ouput" of the PV array, i.e., the nameplate power rating of the array divided by the irradiance for standard test conditions—1000 $W\cdot m^{-2}$—and multiplied by the total annual insolation in the plane of the array). They simulate an AC bus system and a comparable AC/DC bus system, and find that the solar fraction and performance ratio are only 6% lower for the AC bus system. The electricity that must be supplied by the genset is 9% greater, however.

The DC bus configuration has also received attention as of late. Its main attraction is the potential for reduced genset fuel consumption. Because the genset output is rectified immediately, the rotational speed of the genset can vary in response to the load. During part load operation, this will be more efficient than an AC genset, whose rotational speed is fixed by the frequency of the AC output, regardless of the load.

So how does the performance of the AC/DC bus system currently in use compare with that of the AC and DC bus systems? To answer this question, a simulation study of a typical hybrid system was performed (Ross, 2004) with the PVToolbox simulation library for Simulink/MATLAB (Sheriff et al., 2003). The first step in this study was to recreate the results of the Gabler and Wiemken study.

COMPARISON WITH A PREVIOUS STUDY

INPUTS AND PARAMETERS: While Gabler and Wiemken describe their system in some detail, various inputs and parameters had to be assumed in order for the PVToolbox simulation to match their results. These included the input weather file, rectifier and inverter efficiency curves, charge control setpoints, and daily and seasonal variation in the loads. Fortunately, the selection of these inputs and parameters was guided by the detailed simulation performance data Gabler and Wiemken provided, namely, the fraction of the delivered energy at each point in the system. The inputs and parameters were selected on the basis of the AC/DC bus simulation, and then the performance of the AC bus system with the same inputs and parameters used to verify the correspondence of the Fraunhofer and PVToolbox simulations.

The hybrid system of the Gabler and Wiemken study, also used here, consisted of a 9.6 kW genset, a 30.2 kWh battery and a 4 kW PV array (the AC/DC bus system is shown in Figure 4). One year of meteorological data for the German city of Freiburg were used; these data were synthesized using the WATSUN Watgen utility (1992) based on adjusted monthly averages from the nearby city of Stuttgart, provided by Duffie and Beckman (1991). It was inferred that the annual plane of array insolation for the year used in the Gabler and Wiemken study was 1.2 $kWh\cdot m^{-2}$.

The average total daily load was 10.2 kWh, all AC. A 150 W base load accounted for 3.6 kWh per day, or 35% of the average total load. Superimposed on this were square load spikes that together account for the remaining 65% of the load. The maximum load was 1.65 kW. Loads were weighted towards the middle of the day, although load spikes did occur during the night as well. Simulation runs indicated that the daily and seasonal variation in the load significantly influenced the performance of the system. The assumed pattern of variation, which generated results close to those of the Fraunhofer study, was found through a process of trial-and-error.

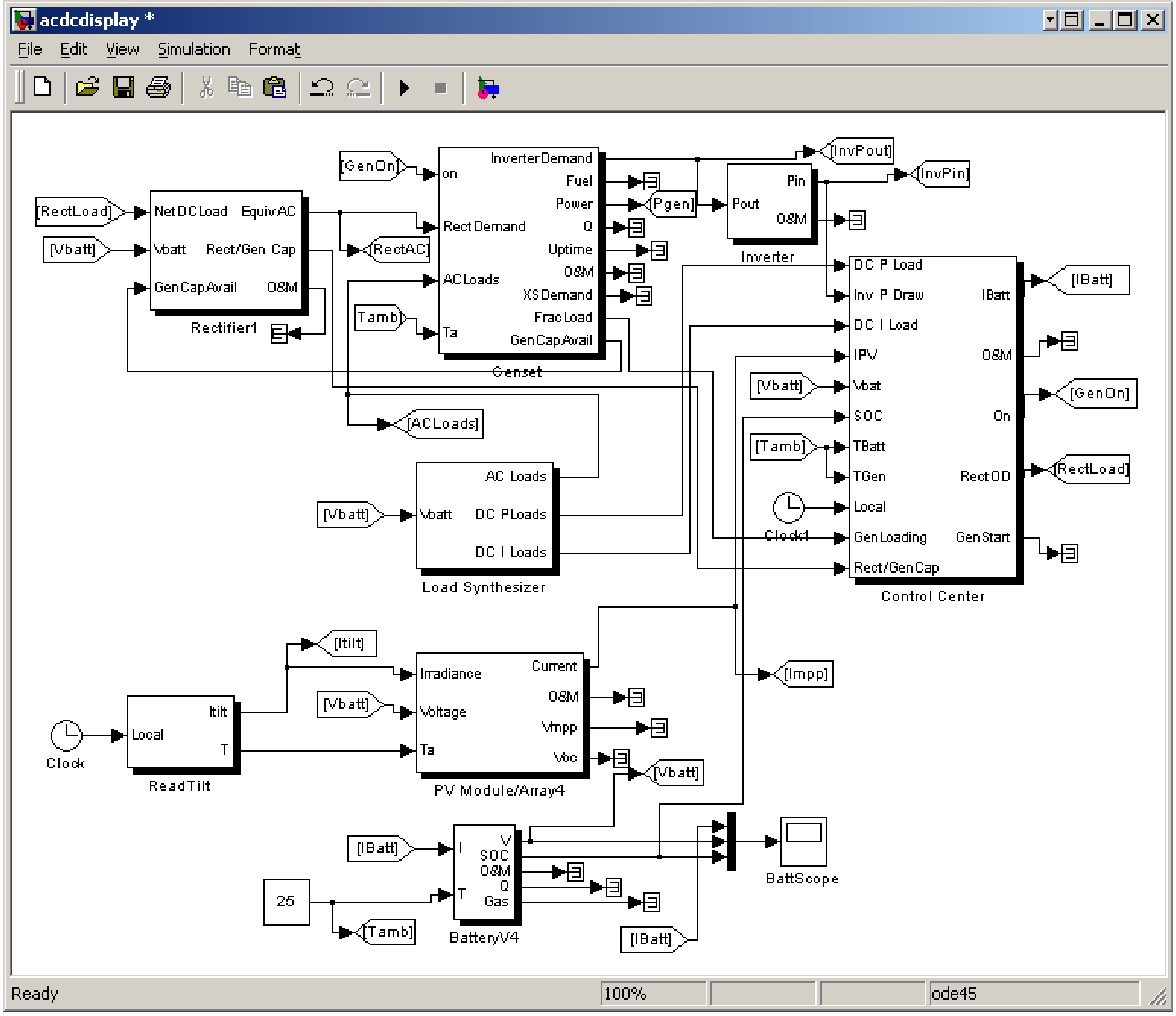

Figure 4: PVToolbox Implementation of the AC/DC Bus Configuration System

The daily load profile was multiplied by a sinusoidal seasonal load factor that reached a minimum of 0.73 around the summer solstice, a maximum of 1.27 around the winter solstice, and unity at the times of the equinoxes. That is, the seasonal variation in the load was perfectly out-of-phase with the length of the day. This seasonal variation improved the correspondence between the PVToolbox results and those of Gabler and Wiemken beyond what was possible though adjustment in the daily load profile.

The peak output of the inverter was 1700 W. Gabler and Wiemken appear to have assumed a very efficient inverter, with efficiency peaking at 95.5% and averaging 94.6%. In contrast, they assumed a very inefficient rectifier, with efficiency peaking at around 79% and an average efficiency of 77.9%. The peak input of the rectifier was 9600 W_{AC}, permitting it to accept the full output of the genset.

In order to match Gabler and Wiemken's results, the charge setpoints had to be fairly high. An absorb voltage of 30.2 V (i.e., 2.52 Vpc) was used. When the absorb voltage was attained, the battery was held at the absorb voltage of 30.2 V for 2.5 hours. Then the charge controller held the battery at the float setpoint of 28.0 V (i.e., 2.33 Vpc) until the available photovoltaic current was insufficient to sustain this voltage. These setpoints pertained to photovoltaic charging only, since the genset cycled the battery between 40 and 70% state-of-charge, except when equalisation occurred. Equalisation, which was triggered every 30 days, caused the genset to start, charge the battery up to 30.2 V, and then hold it there for 8 hours.

With the AC/DC bus system thus configured, performance very close to that of Gabler and Wiemken could be achieved. Given the large number of inputs and parameters that had to be assumed, there was concern, however, that the choice of inputs and parameters might not necessarily be right, but rather just happen to match the output for the case of the AC/DC system.

Although it was not a conclusive test, one way to investigate the choice of input parameters and setpoints was to see how well these components predicted the performance of a different system, namely the AC bus system. Thus the AC bus system was built out of the same components as used in the AC/DC bus system, without changes and the addition of only two components: a maximum power point tracker and an inverter to convert the output of the photovoltaic array to AC.

The tracker was assumed to follow the array maximum power point perfectly, but incur certain power losses within the circuitry used to achieve this. The efficiency approached 98% at no input power, was just under 95% at 4000 W of input power, and varied linearly between these two points. The paralleled module (or string) inverters of the AC bus system were modelled as a single module inverter; it was assumed to have a peak efficiency of 91% at around 1500 W.

RESULTS: For each of the AC/DC and AC bus configurations, Gabler and Wiemken provide total energy flows at over a dozen points in the system that permit a comparison of their simulation results with those from the PVToolbox. This comparison is summarized in Table 1 for the AC/DC bus and Table 2 for the AC bus. These results have been normalized with respect to the total energy consumed by the load: this is set equal to 100. Because the goal of this study was not to compare array models, the array size was adjusted so as to match $E_{mpp,connected}$ for the two studies; hence the difference for this measurement is marked "na". It can be seen that at most points, the two systems are in very close agreement.

There are, however, a few energy flows and losses for which the two simulations differ significantly. The most noticeable is the loss in the principal inverter. In the AC/DC bus system, the difference relative to Gabler and Wiemken is +5.5%. In the AC bus system, it is –15%, a decrement of roughly 20 percentage points. This difference can likely be attributed to the no load consumption of the inverter. In the AC/DC bus system, the principal inverter always sees a load of at least 150 Watts. In the AC bus system, on the other hand, there are times when the output of the module inverter can satisfy the load entirely. Because of this, the no load consumption of the inverter is an important parameter for the AC bus system but not for the AC/DC bus system. It was assumed to be 10 W in both cases, which is likely lower than the figure assumed by Gabler and Wiemken. In any case, it is important to note that in absolute terms, the difference between the inverter losses for the Fraunhofer study and the PVToolbox simulation is only 0.8% of the total energy consumed by the load.

The battery losses for the AC bus system are 7.5% higher in the PVToolbox simulation than in the Gabler and Wiemken study. This is an increment of 4.3 percentage points over the relative difference in the case of the AC/DC bus system. The reason for this discrepancy is unknown; the battery is the most difficult component to model accurately and this may manifest itself in more pronounced differences. In absolute terms, the difference is only 1.2% of the total energy consumed by the load.

The tables are interesting not just as a comparison between the two simulation packages, but also as an itemization of the losses within a hybrid system. Battery losses dominate rectifier losses, which in turn dominate inverter losses. The losses caused by operating the array at the battery voltage rather than its maximum power point are relatively modest, however—about 5 to 9% of the total consumption.

Energy Flow/Loss	Gabler & Wiemken	PVToolbox	Difference (%)	Comment
$E_{nominal}$	131.3	126.3	-3.8	Energy output of PV array if annual insolation occurred at STC with no losses
$E_{mpp,connected}$	110.3	110.0	na	Energy output of PV array operating at MPP with temperature and other losses
$E_{array,Vbat}$	101.7	104.8	3.0	Energy output of array operating at battery voltage
$E_{array,limited}$	84.4	84.4	0.0	Energy output of array reduced by energy wasted by charge control when battery full
$E_{bat+,PV}$	46.4	45.8	-1.3	Energy into battery from PV
$E_{aux\ AC}$	50.3	51.2	1.8	Energy produced by genset
Rect Losses	10.4	10.4	0.0	Losses in rectifying genset output to DC
$E_{bat+,aux}$	36.6	36.9	0.8	Energy into battery from genset
E_{bat+}	83.0	82.7	-0.4	Energy into battery
Batt Losses	18.8	19.4	3.2	Losses in battery: coulombic (gassing), voltage drop, self-discharge
E_{bat-}	64.2	63.3	-1.4	Energy out of battery
Inverter Losses	5.5	5.8	5.5	Losses converting PV & battery output to AC
$E_{PV\ useful}$	70.9	69.5	-2.0	Energy supplied to load coming from PV
$E_{aux\ useful}$	29.1	30.5	4.8	Energy supplied to load coming from genset
$E_{consumer}$	100	100	na	Energy supplied to load
Solar Fraction	0.71	0.70	-1.4	Fraction of load supplied by PV
Perform. Ratio	0.54	0.55	1.9	Fraction of Enominal actually used by load

Table 1: Comparison of Energy Flows for AC/DC Bus System

Energy Flow/Loss	Gabler and Wiemken	PVToolbox	Difference (%)	Comment
$E_{nominal}$	131.3	127.5	-2.9	Energy output of PV array if annual insolation occurred at STC with no losses
E_{mpp}	114.8	115.6	0.7	Energy output of PV array with perfect lossless maximum power point tracking
$E_{mpp,connected}$	110.4	111.0	na	Energy output of PV array operating at MPP with temperature and other losses
$E_{array,limited}$	100.7	100.5	-0.2	Energy output of array reduced by energy wasted by charge control when battery full
$E_{bat+,PV}$	54.1	51.8	-4.3	Energy from PV array at input to rectifier
$E_{aux\ AC}$	54.6	55.2	1.1	Energy produced by genset
Rect Losses	23.0	23.3	1.3	Losses rectifying array, genset output to DC
$E_{bat+,aux}$	50.5	51.6	2.2	Energy from genset at input to rectifier
E_{bat+}	81.6	80.1	-1.8	Energy into battery
Batt Losses	16.1	17.3	7.5	Losses in battery: coulombic (gassing), voltage drop, self-discharge
E_{bat-}	65.5	62.8	-4.1	Energy out of battery
Mod Inv Losses	11.0	11.2	1.8	Losses in converting module output to AC
Inverter Losses	5.2	4.4	-15	Losses in converting battery output to AC
$E_{PV\ useful}$	66.8	66.3	-0.7	Energy supplied to load coming from PV
$E_{aux\ useful}$	33.2	33.7	1.5	Energy supplied to load coming from genset
$E_{consumer}$	100	100	na	Energy supplied to load
Solar Fraction	0.67	0.66	-1.5	Fraction of load supplied by PV
Perform. Ratio	0.51	0.52	2.0	Fraction of Enominal actually used by load

Table 2: Comparison of Energy Flows for AC Bus System

AC BUS VERSUS AC/DC BUS

As mentioned earlier, Gabler and Wiemken comment that “in spite of the additional transforming processes, the AC-coupled system is not far away in performance…from the DC system”. But is the AC bus system really so comparable in performance to the AC/DC bus configuration? Intuitively, the additional DC to AC and subsequent AC to DC conversion of that portion of the array’s output destined for the battery should lead to significant additional losses. Why do these losses not appear more significant in Gabler and Wiemken’s work?

Gabler and Wiemken emphasize the performance ratio and solar fraction as performance metrics. While these metrics are useful to the engineer interested in determining how well the system is utilising available solar energy, in reality, most hybrid power system owners and operators are more interested in satisfying their power requirement at minimum cost. If we consider the design and operation of the systems as a given, then the significant metric for comparison is not performance ratio nor solar fraction, but rather the energy that the engine-driven generator must provide: this will strongly influence the fuel consumption. And, as observed earlier, Gabler and Wiemken find that the AC bus system is 5 to 6% worse than that of the AC/DC bus system in terms of the solar fraction or performance ratio, but 8 to 9% worse in terms of the electricity supplied by the genset.

Furthermore, Gabler and Wiemken’s choice of two components is somewhat surprising. The rectifier has a significantly lower efficiency than the principal inverter, and a maximum power point tracker is included in the AC bus system but not the AC/DC bus system.

The average efficiency of the principal inverter exceeds that of the rectifier by more than 15 percentage points. In their paper Gabler and Wiemken investigate how raising the average rectifier efficiency to 90% affects the system performance. The present study examines how changing the rectifier efficiency curve to one comparable to that of the principal inverter affects the results.

Gabler and Wiemken’s inclusion of maximum power point tracking in their AC bus system but not their AC/DC bus system probably reflects typical systems: most AC/DC bus systems have the array voltage fixed by the battery, whereas AC bus systems will have a maximum power point tracker built into the module inverter. But this is not a fair comparison: the performance improvement realised by the AC bus system due to maximum power point tracking was not free—it had to be paid for in the form of the module inverter. For less cost, the AC/DC bus system could use a charge controller with maximum power point tracking. This represents a more logical and fairer comparison, though it is still imperfect since the capital cost of the AC bus system, with its additional inverter circuitry, will still be higher. To redress this imbalance, maximum power point tracking (MPPT) was added to the AC/DC bus comparison for subsequent comparisons.

Table 3 compares the AC and the AC/DC bus systems by solar fraction, performance ratio, and AC electricity required from the genset (normalized in relation to the total consumption of the load). Improving the rectifier efficiency mainly benefits the AC bus, as noted by Gabler and Wiemken. This makes sense since in the former system, all energy destined for the battery must pass through the rectifier, whereas in the latter case, only the output of the genset that is destined for the battery passes through the rectifier. The improvement appears mainly in the electricity that must be supplied by the genset.

	Solar Fraction			**Performance Ratio**			**Genset Output (Total Load =100)**		
	AC/DC	**AC**	**Diff**	**AC/DC**	**AC**	**Diff**	**AC/DC**	**AC**	**Diff**
Gabler&Wiemken	0.695	0.663	-4.6%	0.550	0.520	-5.5%	51.2	55.2	7.8%
Better rectifier	0.697	0.685	-1.7%	0.552	0.541	-2.0%	43.5	44.6	2.5%
AC/DC has MPPT	0.726	0.663	-8.7%	0.574	0.520	-9.4%	46.6	55.2	18.5%
Better rectifier+MPPT	0.726	0.685	-5.6%	0.574	0.541	-5.7%	39.6	44.6	12.6%

Table 3: Effect of Higher Rectifier Efficiency and MPPT for AC/DC Bus System on System Performance, Results from PVToolbox Simulations

With an improved rectifier, the performance of the AC bus system is very close to that of the AC/DC bus system—that is, until one considers the impact of adding maximum power point tracking to the AC/DC bus system. The energy that must be provided by the genset in the AC bus system is 19% higher with the original rectifier and 13% higher with the more efficient rectifier. Thus the performance of the AC bus system is considerably worse than that of the AC/DC bus system, at least for the assumed load and array size.

SENSITIVITY TO LOAD PROFILE AND SIZE OF ARRAY

What is the sensitivity of the performance of the two system configurations to changes in the daily and seasonal variation in the load? Are the above conclusions valid for larger and smaller arrays? This was investigated by rerunning the simulation with various daily load profiles and a range of array sizes.

To test sensitivity to seasonal variation in the load, three simulations were run. The daily load profile consisted of a base load plus peak loads with profiles repeating on a 4, 6, and 12 hour basis. This was intended to be a neutral load profile, emphasizing neither day nor night loads. Two of the simulations scaled this daily profile by a sinusoid with a period of one year. One had summer solstice loads 27% higher than equinox loads and the winter solstice loads 27% higher than equinox loads. In the third simulation the daily load profile was constant year round. A high efficiency inverter and MPPT were included in both systems.

These simulations revealed that regardless of whether loads are constant year round or weighted towards summer or winter, the AC bus system needs more electricity from the genset than the AC/DC bus system. Both the AC and the AC/DC bus systems require less energy from the engine-driven generator when loads are higher in the summer and lower in the winter, as expected. Since the absolute difference between the energy required by the AC bus system and the AC/DC bus system changes little, the relative difference increases when loads are heavier in summer. In relative terms, the AC bus system required roughly 12 to 18% more energy from the genset than the AC/DC bus system. Similar tendencies held for the solar fraction and performance ratio.

The simulation without seasonal variation in the load was then rerun with four different load profiles, in addition to the “neutral” profile used already. One had only day loads, another only night loads, and the remaining two had loads throughout the day but weighted mainly towards day or night.

The results are shown in Figure 5: the electricity required from the genset falls the more loads are concentrated during the daytime. The AC/DC bus system outperforms the AC bus system by 10 to 16%, although the difference tends to be less pronounced in relative and absolute terms the more loads are weighted towards the daytime. This probably stems from daytime loads being met directly by the module inverter, reducing losses in rectification for storage in the battery. Similar tendencies are evidenced in the solar fraction and performance ratio.

To investigate the sensitivity of these results to the array to load ratio, the array size was varied over a wide range (no array to 13,200 W_p array), with a “neutral” load and no seasonal variation. The module inverter and the maximum power point tracking losses were scaled in proportion to the array size.

For all array sizes, the AC bus system requires more energy from the engine-driven generator than the AC/DC bus system. As the array size increased from 0, the additional energy required by the AC bus system (relative to the AC/DC bus system) rose roughly linearly, up to around 2500 W_p of array capacity. With array sizes larger than this, the relative difference is in the range of 11 to 19%.

While a similar tendency applied to the solar fraction, the difference between performance ratios was most pronounced with small arrays. With no array output rejected, the higher efficiency of the AC/DC bus system is apparent. PV output that can be used directly by the load passes through the 95% efficient principal inverter in the AC/DC bus system but the 90% efficient module inverter in the AC bus system. The remainder of the output, destined for the battery, suffers from two power conversion stages in the AC bus system but only wiring losses in the AC/DC bus system. With large arrays, the lower power conversion losses of the AC/DC bus system are swamped by the losses associated with rejecting available array output; the performance ratios of the two systems converge.

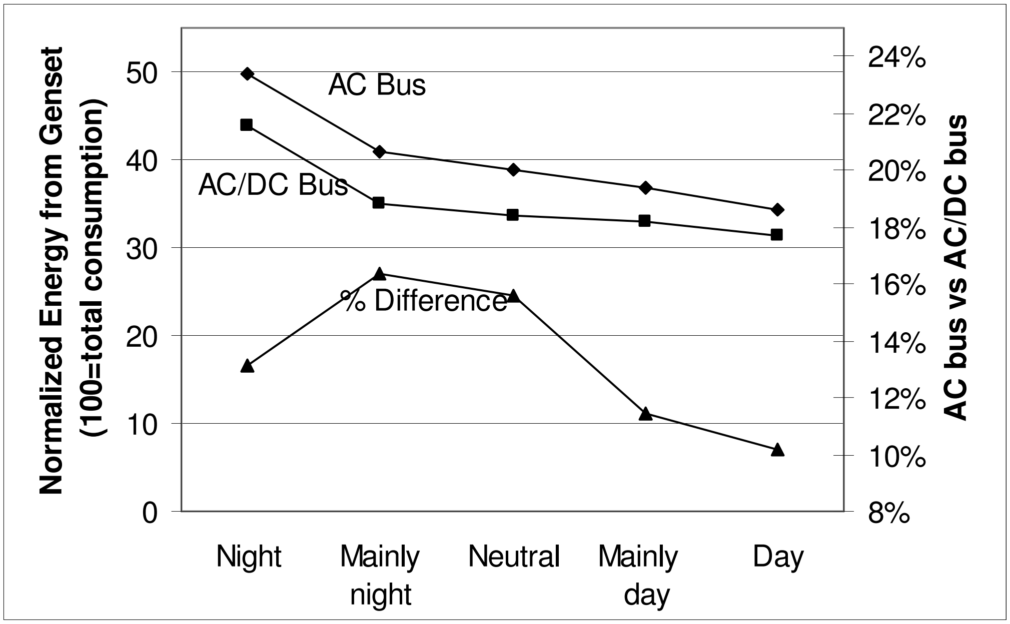

Figure 5: Sensitivity of Genset Electricity Requirement to Diurnal Load Variation

COMPARISON WITH DC BUS

The AC and AC/DC bus systems can also be compared to the DC bus system. In the PVToolbox, the DC bus system is modeled very similarly to the AC/DC bus system. Only two changes are necessary: first, the AC loads draw power from the inverter, and are not transferred to the genset when it turns on. Second, the variable speed operation of the genset results in a different curve for fuel consumption versus output. A high efficiency rectifier and MPPT are assumed.

Due to the paucity of data for the fuel consumption of variable speed gensets, the fuel curve is idealized here. The AC genset is assumed to have a full load fuel consumption of 0.5 litres of diesel per kWh, or 4.8 l/hour. Its no load consumption is 25% of this, or 1.2 l/hour; between no load and full load the fuel consumption varies linearly between 1.2 and 4.8 l/kWh. In contrast, for the DC genset the full load fuel consumption is the same, but the no load fuel consumption is assumed to be 0, and the fuel consumption again varies linearly between these two points.

Electricity destined for the battery or DC loads (discussed later) suffers the same losses in rectification for both the variable speed and the fixed speed genset. This assumption is based on the similarity of the transformation processes. In the variable speed genset, a regulation circuit controls the field current in an alternator to achieve the desired voltage at the output of a diode bridge. In the fixed speed genset, a similar regulation circuit controls the field current in a synchronous generator (in terms of losses, this should resemble an alternator) to maintain a stable AC voltage. This is in turn chopped by SCRs that vary their duty cycle in response to changes in demand. During conduction, losses in an SCR are comparable to those of a diode. There are additional losses associated with switching the SCR on, but this occurs only once every half cycle. Thus, in both topologies, we have a field current regulation circuit, “AC generator”, and rectification circuitry.

Five different scenarios are considered. The first “baseline” scenario assumes the seasonal and diurnal load pattern found to fit the Gabler and Wiemken study. In the second scenario, no equalisation charging is done: the engine-driven generator is not run for an additional 8 hours every 30 days simply to equalise the battery. In the third scenario, the load profile is changed. Now the 10.2 kWh daily load occurs in two one-hour spikes of 5.1 kW, one starting at midnight and the other at noon. In the fourth, loads are split equally between AC and DC loads. For even hours, the load is DC and for odd hours it is AC. In the fifth scenario, the entire load is DC, having the same variation as the baseline load. The three bus configurations are compared in terms of the energy required from the genset (Table 4), annual fuel consumption (Table 5), and annual genset run time (Table 6).

In the baseline scenario the DC bus system performs very similarly to the AC/DC bus system except that its fuel consumption is about 12% lower, due to the variable speed operation of the genset. The AC bus system requires about 12% more energy from the genset than the AC/DC bus system, and consumes 11% more fuel. The difference arises because fuel consumption is not proportional to energy required: during equalisation, the genset operates at part load and fuel consumption is not greatly reduced.

	AC/DC Bus	**AC Bus**		**DC Bus**	
	Total=100	**Total=100**	**% Diff**	**Total=100**	**% Diff**
Baseline	39.7	44.6	12.3%	40.0	0.7%
No equalisation	36.2	41.3	14.1%	37.1	2.6%
5.1 kW AC load	41.1	47.4	15.3%	42.0	2.3%
AC & DC loads	38.0	44.7	17.7%	38.2	0.5%
DC loads	36.0	42.5	18.2%	35.9	-0.3%

Table 4: Annual Energy Required from Genset (% Differences relative to AC/DC Bus)

The effect of the part load operation during equalisation is eliminated in the second scenario (equalisation turned off). Now the genset runs at full power to charge up the batteries to 70% state-of-charge, and then shuts off. Thus, the variable speed genset is not advantageous, because its fuel consumption at full load is assumed to be equal to that of the fixed speed genset. Under these assumptions, the DC bus system requires about 2.6% more electricity from the genset than the AC/DC bus system. The additional 2.6% of electricity is matched by 2.7% higher fuel consumption and 2.6% longer run-time, as expected. Similarly, the 14.1% higher genset electricity requirement of the AC bus system (compared to the AC/DC bus system) is matched by 13.9% higher fuel consumption and 14.0% higher runtime (differences may be attributed to round-off and simulation inaccuracy).

Comparison of the scenario without equalisation with the baseline scenario demonstrates that these systems consume a significant portion of their fuel in part load operation during equalisation. When equalisation is turned off in the AC/DC system, the energy required from the genset falls by only 9% but the fuel consumption plummets by 20%. Even with the variable speed genset, the reduction in fuel consumption is 7%. Thus minimising the use of the genset for equalisation should be a criterion for intelligent genset dispatch.

	AC/DC Bus	**AC Bus**		**DC Bus**	
	l diesel	**l diesel**	**% Diff**	**l diesel**	**% Diff**
Baseline	844	935	10.8%	746	-11.6%
No equalisation	675	769	13.9%	693	2.7%
5.1 kW AC load	869	987	13.6%	782	-10.0%
AC & DC loads	814	938	15.2%	712	-12.5%
DC loads	776	899	15.9%	669	-13.8%

Table 5: Annual Fuel Consumption (% Differences relative to AC/DC Bus)

One might expect that the AC/DC bus and AC bus systems would have a performance edge when large AC loads were the norm: the genset output could be used directly for these loads, unlike in the DC bus system. But the difference is not particularly significant, as demonstrated in the third scenario. Compared to the AC/DC bus system, the DC bus system requires only 2.3% more electricity from the engine-driven generator. As a result, the DC bus system uses 10% less fuel than the AC/DC bus system. This reflects that the genset is operating only 3% of the year. Thus most of the time the high AC loads draw from the battery. If the solar fraction was considerably lower, the AC/DC bus and even the AC bus system might appear more attractive.

Conversely, in the fourth and fifth scenario, the load is partly and wholly DC, respectively. In absolute terms, the fuel consumption of all systems is reduced, since losses in the inverter are reduced. Relative to the AC/DC bus system, the performance of the DC bus system improves slightly and that of the AC bus system deteriorates, simply because the denominator (the AC/DC bus fuel consumption) is falling. When looking at the genset energy requirement or the runtime, we see the performance of the DC and AC/DC bus systems converging as loads shift to DC.

	AC/DC Bus	**AC Bus**		**DC Bus**	
	Days	**Days**	**% Diff**	**Days**	**% Diff**
Baseline	10.1	10.8	7.9%	10.1	0.5%
No equalisation	5.9	6.7	14.0%	6.0	2.6%
5.1 kW AC load	10.3	11.3	9.9%	10.4	1.4%
AC & DC loads	9.8	10.8	10.9%	9.8	0.2%
DC loads	9.5	10.5	11.1%	9.5	-0.2%

Table 6: Annual Genset Runtime (% Differences relative to AC/DC Bus)

In reality, the reduction in the fuel consumption associated with a variable speed genset will likely be less than found here, for two reasons. First, the once-per-month 8 hour genset-powered equalisation assumed here is probably longer than actually required, and during summer may be supplanted by equalisation powered solely by the photovoltaic array. The advantage of the variable speed genset appears only when it is operated at part load, and with less equalisation the fraction of the genset's operation that occurs at part load will be reduced. As seen in the second scenario, without genset-powered equalisation, the variable speed genset is not attractive.

A second reason for the supposition that the real fuel consumption reductions associated with the DC genset will be less than the 10% to 14% estimated here is the optimistic nature of the fuel consumption curve for the variable speed genset. Here an ideal variable speed genset was assumed: its no load consumption is zero. Real variable speed gensets will consume some fuel at no load, and this influence will be seen at all loading levels.

CONCLUSIONS

The PVToolbox was used to compare the operation of three bus configurations for photovoltaic-genset hybrid systems: a conventional AC/DC bus, an AC bus, and a DC bus. The simulations used one year of synthesized weather data for Freiburg, Germany, and extended an earlier study conducted by Gabler and Wiemken (1998). The PVToolbox was able to recreate Gabler and Wiemken's simulation results very closely.

Gabler and Wiemken emphasize the performance ratio and the solar fraction as metrics of system performance. On the basis of these metrics, they conclude that the AC bus system is comparable in performance to the AC/DC bus system. Here we assert that, since it will be closely related to the fuel consumption, the electricity required from the genset is a more important metric. In addition, Gabler and Wiemken assume 1) a very inefficient rectifier but an extraordinarily efficient inverter and 2) that the AC bus system will have maximum power point tracking but the AC/DC bus system will not. With the rectifier efficiency improved to match that of the inverter, and both systems benefiting from maximum power point tracking, the performance ratio and solar fraction of the AC bus system are about 6% lower than for the AC/DC bus system, but the electricity required from the engine-driven generator is around 13% higher. This suggests that the AC/DC bus system performs significantly better than the AC bus system. Further simulations revealed that this conclusion is insensitive to the seasonal and diurnal profile of the load and the size of the photovoltaic array.

In this study, variable speed genset operation offered a 10 to 14% reduction in the fuel consumption compared to a fixed speed genset used in an AC/DC bus system. On the other hand, eliminating the 8-hour, genset-powered equalisation that occurs every 30 days reduces the fuel consumption of the fixed speed genset by 20%. This suggests that variable speed genset operation may be less effective at reducing fuel costs than more intelligent dispatch strategies that reduce the time that the genset is operating at part load or that improve the utilisation of solar energy. This is especially true given that this study used an optimistic curve for the fuel consumption versus output curve of the variable speed genset.

Thus, the conventional AC/DC bus system offers some compelling advantages compared to either AC or DC bus systems. It can satisfy AC loads directly, unlike a DC bus system, and its fuel consumption suffers only during part load operation. If intelligent dispatch can minimize the time spent during part load operation, the fuel consumption may even be lower than that of the DC bus system.

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