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A 10 kW COMBINED HYBRID (WIND AND SOLAR PHOTOVOLTAIC) ENERGY SYSTEMS FOR ISOLATED GENERATING SYSTEM

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ABSTRACT

There is a potentially vast world market for stand-alone power sources. In rural districts of the developing world, the energy consumption per capita is very low and basic energy needs are for water pumping, electricity supplies to small hospitals, lighting, cooling and telecommunications. Often the cost of connection to the grid in remote locations cannot be justified. Photovoltaic and wind power can meet these needs, but either source alone provides an intermittent supply and energy storage is needed to deliver a reliable supply. However, these two sources are complementary since sunny days are usually calm and strong winds are often accompanied by cloud and may occur at night. A combined plant, therefore, has higher availability than either individual source and so needs less storage capacity. A stand-alone electrical supply system is described which combines the output of wind and solar Photovoltaic generating systems. The experimental system comprises wind and solar collectors, each of 5 kW rating, with a lead-acid battery for storage and a 10 kW PWM inverter for the final output. The wind turbine generator is a 200 rpm, direct drive, permanent-magnet, axial-flux machine based on the 'Torus' configuration. Its three-phase output is rectified to form a variable-voltage dc link. The power converter uses two dc-dc converters connected in series, each with a bypass diode which conducts continuously when the corresponding source is not available. For all load demands the levelised energy cost for PV-wind hybrid system is always lower than that of standalone solar PV or wind system. The PV wind hybrid option is techno-economically viable for rural electrification.

Keywords: power source, hybrid energy system, solar photovoltaic generating system, wind power, isolated, rural electrification.

1. INTRODUCTION

There is a potentially vast world market for stand-alone power sources. In rural districts of the developing world, the energy consumption per capita is very low and basic energy needs are for water pumping, electricity supplies to small hospitals, lighting, cooling and telecommunications. Often the cost of connection to the grid in remote locations cannot be justified. Photovoltaic and wind power can meet these needs, but either source alone provides an intermittent supply and energy storage is needed to deliver a reliable supply. However, these two sources are complementary since sunny days are usually calm and strong winds are often accompanied by cloud and may occur at night. A combined plant, therefore, has higher availability than either individual source and so needs less storage capacity.

2. SYSTEM DESCRIPTION

The prototype system has the following target specification. However, the plant could easily be modified to provide a single-phase output or to utilize a different proportion of wind and solar energy according to local circumstances and needs.

Overall system

Rated output power: 10kW at 380V, three phase, 50Hz

Wind turbine

Rated electrical output power:	5kW at 150 V dc
Turbine diameter :	5 m
Turbine speed :	100-200 rpm

Available space for machinery approximately 500 mm diameters

Target for the generator design are low cost and high efficiency.

Solar panel

Rated electrical output power: 5kW at 150 V dc

The overall arrangements of the plant are illustrated in Figures 1 and 2. The heart of the system is the double-input, single-output dc power conditioner.

3. PROTYPE COMPONENTS

3.1 PV array

The PV array uses 14 parallel strings of eight series-connected standard modules. A module comprises 36 polycrystalline silicon cells housed in an aluminium frame with polyester back and glass front covers. The array voltage is 168V on open-circuit falling to 136V at the design power of 5kW. The mean efficiency is 13%. For maximum energy capture, the array should be tilted from the horizontal and the angle at 20^o during the summer and 60^o in winter. It was calculated that acceptable energy production would be achieved.

3.2 Wind turbine generator design

The wind turbine section of the plant is to use a directly-coupled generator. In recent years a number of direct drive concepts have been proposed or tried [1]. Hydro-type synchronous generators with wound poles for a vertical-axis 4MW turbine and for the Enercon 500kW production machine. Small battery charging machines use an ironless-stator, axial-flux, permanent-magnet generator. Proposals for direct-coupled grid-connected generators include transverse-flux and radial flux permanent-magnet machines. The 'Torus' configuration [2,3] illustrated in Figures 3 and 4 which is an axial-flux permanent-magnet machine using a slot less toroidal-wound iron-cored stator and selected for the present application. UMIST had responsibility for production and testing of the generator.

3.3 Materials

Several types of permanents-magnet material have been used in electrical machines including Alinico metal alloys in pilot exciters for large turbine generators, ferrite for small low-cost motors and rare-earth alloys such as Nd-Fe-B used in compact high-performance motors. For minimum cost, ferrite would be preferred but in order to meet the diameter restriction and the target for high efficiency Nd-Fe-B is found to be necessary.

3.4 Dimensions

A Torus machine design is characterized by the stator core outside and inside diameters, the winding conductor size and number of turns, the pole number, the magnet thickness and material type. The remaining dimensions and parameters can be determined given values for these quantities. The number of layers of turns needed to form each coil has an important influence on the ease of the winding the stator. The cost of the machine includes material and manufacturing costs. The principal material cost is attributed to the magnets themselves if Nd-Fe-B is used.

3.5 Losses and efficiency

The efficiency is determined by the losses, the principal components being:
I^2R loss in the stator winding
Eddy current loss in the air gap-wound stator conductors
Iron loss in the stator core
Friction and wind age

The loss at low intermediate power is important because the wind turbine spends only a small proportion of its working life at full power. In the present system, however, reduced-speed operation at low power reduces the iron and other losses which are independent of load current there by greatly improving the part-load efficiency. The system permits variable-speed operation with shaft power propositional to speed. The generated voltage is propositional to speed and so the current is propositional to speed and the I^2R loss is propositional to speed. At low speed the I^2R loss is there fore less important. Eddy current loss varies as speed, flux density and wire diameter. At low power, the eddy current loss becomes increasingly important, but in the present design it is very low because thin wire is used. Iron loss varies approximately in proportion to speed. Rectifier loss is propositional to the DC current and hence speed^2 Being a direct-coupled machine, the wind age and friction losses are very small. Losses also determine the winding temperature but the need for high efficiency is a more stringent restriction.

3.6 Prototype design

Many designs were studied using a computer program embodying electric, magnetic and thermal models. The most favorable of those meeting the specification is described by the leading parameters given in Table-1. The magnet thickness was later increased to 12.7 mm to utilize a standard block. Designs using ferrite magnets were sought but no satisfactory solution was obtained within the diameter constraint. However satisfactory solutions do exist for diameters above 650 mm. The predicted efficiency over the operating power range is given in Table-2 taking account of the speed and power variation of the loss components as discussed above.

4. CONSTRUCTION AND TESTING

The prototype machine is, to the best of the authors' axial forces of attraction which becomes critical in large machines. Ideally, the forces balance but adequate stiffness is needed for stability of the 1.5mm rotor-stator clearance. Also, a controlled assembly procedure using jacking screws was needed to resist the attractive force of 10kN due to the air-gap flux density of 0.69T. For testing, the generator was driven by a d.c. motor through three stages of speed reduction, using belts for the first two stages and a final chain drive to transmit the high shaft torque of the generator. A torque transducer was fitted on the input shaft to the final drive. Figure-4 shows components of the generator and Figure-5 shows the generator test rig in the UMIST laboratory. Open circuit wave shapes were found to be very close to sinusoidal for line and phase voltage and for a single-turn coil on the stator core. Harmonic analysis of the line voltage waveform showed that the largest harmonic component, the fifth, was only 0.6%. Generator performance was measured under a range of condition [3]. Figures 6 and 7 give the measured performance at the nominal speed of 200 rev/min with rectifier-resister load. The d.c. output voltage were 139 V on no-load and 107V with rated 5kw load. These were somewhat less than the predicted values owing to variations of some details compared with assumptions made at the design stage. The reduced value of output voltage required increased current (47) at the rated output [power. However, the measured efficiency was 80.7% at this point, exceeding the design prediction of 79.4% even though the latter figure did not include losses in the rectifier and chain drive. This improvement was attributed to the observed sinusoidal wave shape of induced emf which produced a winding current with improved form factor.

5. POWER AND CONVERSION STORAGE

5.1 Design of DC power conditioner

The dc power conditioner, Figure-1, uses two step-up converters with their outputs is series. Bypass diodes conduct continuously when the corresponding input source is not available. The design is constrained by stresses on the components due to switching of the two main devices. Analysis of modes of operation [4, 5] shows that the worst case occurs when only one of the two sources is operating and the battery supplies the load at nominal voltage. This leads to the highest peak current in bath the inductors and the power semiconductors and results in the highest rms current ripple in the output capacitors. These values of voltage and current are used for the selection of power switches and output capacitors, the design of inductors and the prediction of power loss needed for the design of the cooling system.

5.2 Selection of power semiconductors

Either MOSFTs or IGBT s would be should at this power rating and their costs and drive requirements are similar. IGBTs were selected for their lower voltage drop. A switching frequency of 15 kHz was adopted as a compromise between IGBT power dissipation and size of passive components.

5.3 Design of ferrite-core inductors

Inductors rated 850 uH, 40 A are needed for the input circuits and were designed and built to suit. Gapped ferrite cores are usual in such applications to minimize inductor size and losses. The core is assembled from eight ferrite cores and an adjustable gap is provided to trim the inductance to the desired value.
The winding has 44 turns in 4 layer.

5.4 Selection of output capacitors.

Electrolytic capacitors were selected to provide the required capacitance and voltage and rms current ratings. To meet the target for acceptable heating due to the capacitor ESR loss, each step-up converter stage of the 10 kW prototype uses 3 parallel capacitors each rated 2200 uF - 450 V.

5.5 Cooling system design

Design of the cooling system is based on the predicted converter power loss. Assuming rated input of 150 V, 33 A from each generating unit, it was calculated that the input converters have about 97% efficiency. They drop to about 95% with one unit idle because of increased IGBT conduction loss at the higher duty cycle. For natural convection, the power switches are to be mounted on an aluminum heat sink with thermal resistance of 0.15^{o}C/W to air. Since the inductors and capacitor are housed inside the converter frame, internal air circulation is important and is created by two low-power fans controlled by a temperature sensor.

5.6 Laboratory testing

A laboratory test rig was built using variable transformer-rectifier power supplies to emulate the PV array and the wind generator. A dc load was arranged by using a 300 V lead-acid battery and available power resistors. Initial tests were carried out to evaluate a single input converter operation via the bypass diode of the other converter. Tests showed that the input current ripple was less than 20% of the average current, which leads to acceptable converter losses with a reasonably sized input inductor. Performance was also evaluated with both input circuits active. These tests were carried out using the actual values of input voltage and current resulting from the design and construction of the two generating units. The reduced values of the input voltages at which the wind and PV units deliver the 5kW rated power (i.e. 107V and 136V, respectively) required increased input currents, leading to reduced efficiency in the converter. The efficiency achieved by the converter unit remained between 94% and 95% over a wide power range. Single converter tests were conducted across a range of input powers from 500W to 5kW. It was found that with 5kW input power and a duty-cycle of 0.5 for the IGBT each dc-dc converter had efficiency slightly better that 95%, which was in good agreement with the predicted value.

5.7 Battery selection

A 150Ah, 300V storage battery was selected for a field test programme. The voltage was chosen to cause the input converters to operate with acceptable duty cycle and the capacity was chosen with a view to envisaged applications of such combined wind/ PV generating systems.

5.8 Output inverter

The output inverter is required to produce a sinusoidal output voltage waveform with fixed both amplitude and frequency. Single-phase or three-phase applications will arise. Suitable sinusoidal PQM inverters are commonly used for uninterruptible power supplies therefore no development is needed in this area. The project has therefore concentrated on the provision of the dc power and its delivery to the main dc link and testing has been carried out suing dc loads.

5.9 Pro type plant tests

After laboratory testing of the novel components the 10kW prototype was assembled at the WEST factory in Taranto, Italy. During a typical test sequence the PV unit delivered about 1.1 to 4.1kW/ Tests showed that the efficiency of the d.c. power conditioner remained between 94 and 95% over the output power range from 3.7kW to 6.7kW.

Table-1. Principal dimensions.

Pole number	**28**
Winding layers	4
Stator core outer dia.	465 mm
Stator core inner dia.	275 mm
Stator core thickness	10 mm

Table-2. Efficiency and power over the speed range.

Speed rpm	**200**	**180**	**160**	**140**	**120**	**100**	**80**	**60**
Shaft power kW	6.41	4.67	3.28	2.20	1.38	0.80	0.41	0.173
Output power kW	5.08	3.73	2.66	1.81	1.14	0.66	0.33	0.129
Efficiency %	7.3	7.8	81.1	82.1	82.6	82.3	80.7	74.5

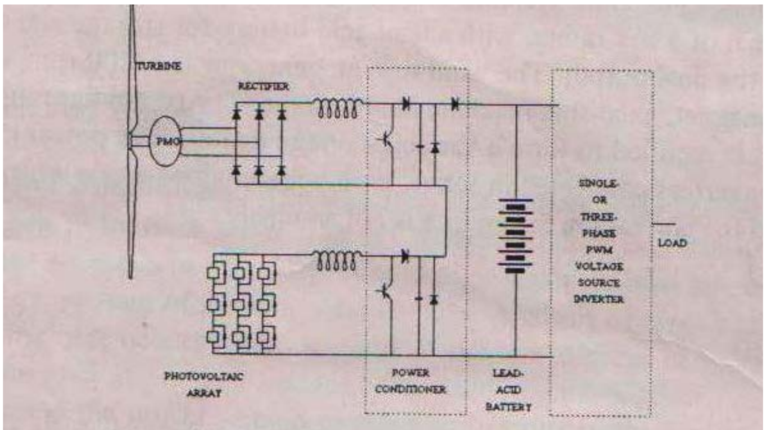

Figure 1 Overall plant electrical arrangement

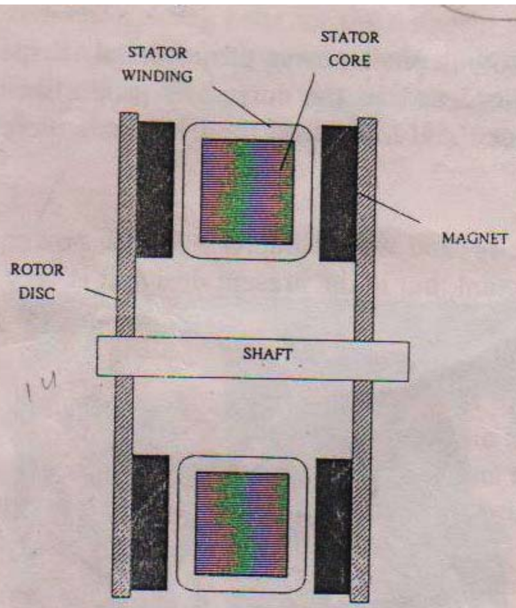

Figure 2 The 'Torus' machine arrangement

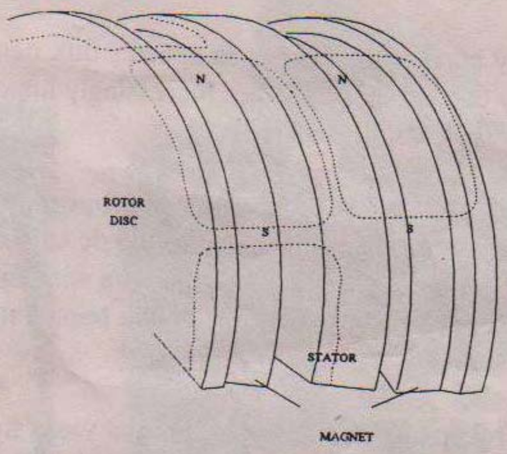

Figure 3 Flux paths in the 'Torus' machine

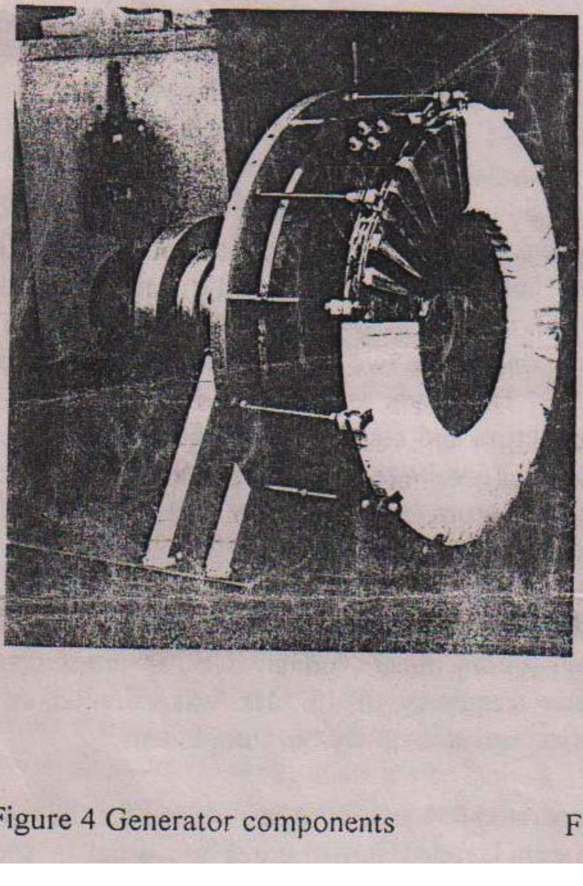

Figure 4 Generator components

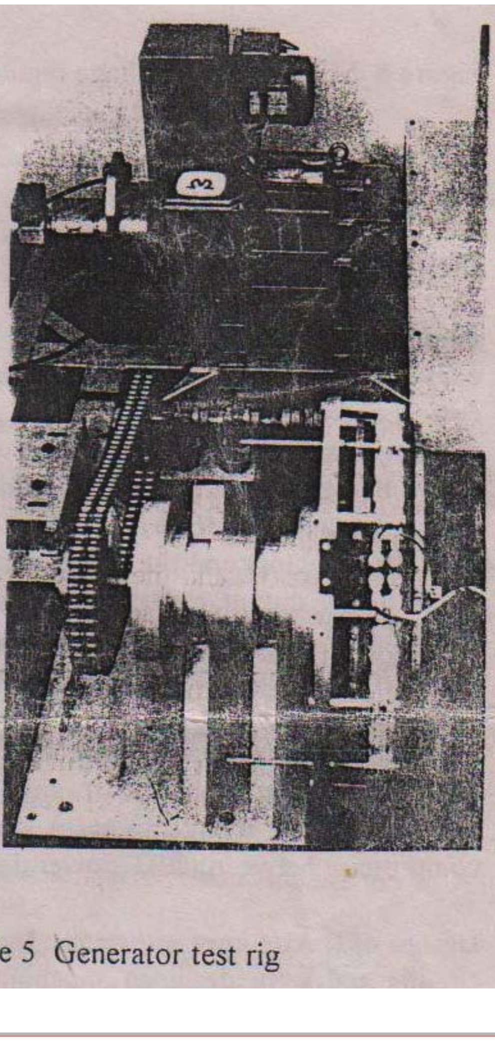

Figure 5 Generator test rig

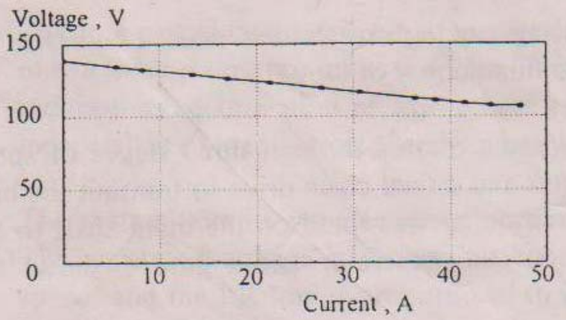

Figure 6 Measured d.c. voltage regulation with resistive load

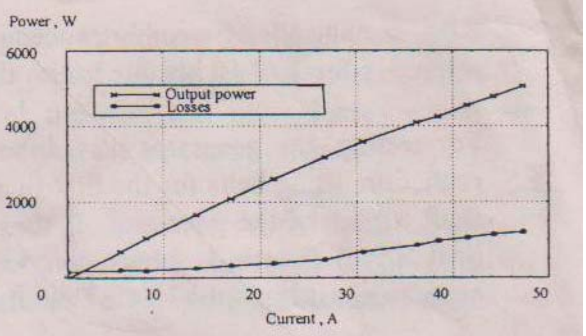

Figure 7 Measured variations of d.c. output power and losses with resistive load

6. CONCLUSIONS

The design and construction and test of the prototype components of a 10kW pilot plant have been described. Unconventional solutions adopted for the wind generator and the power conditioner have been outlined.

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