Double-port Interface for Small Scale Renewable Sources Integration

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***Abstract*— Integration of renewable energy sources such as wind power and solar photovoltaic is an ongoing research worldwide. In this paper a hybrid power electronics interface that combines the energy from solar photovoltaic panel and wind generator into a small scale stand-alone system is proposed. Several other works have proposed a parallel injection of various renewable energy sources on a single DC-bus. This paper proposes a double-port boost-buck-boost (BBB) topology that enhances the power capability of the PV-Wind power system during partial solar irradiation and weak winds. After the description of operation of this double-port interface, a simulation model for 1 kW PV array integrated together with a 1.5 kW wind generator was developed and simulation results presented.**

***Index Terms*— Renewable sources, Power Electronics Interface, MPPT, Wind generator, PV array**

I. Introduction

While the global demand of energy is increasing constantly, the use of classic source of energy like oil and coal becomes problematic contributing among other things to climate change. One solution to address climate change is the use of clean renewable energy sources among other solar and wind.

Most areas in South Africa average more than 2500 hours of sunshine per year with an annual 24 hour solar radiation of approx 220 W/m^2, compared with 150 W/m^2 in the USA and averaging 100 W/m^2 for Europe. This makes South Africa's solar radiation resource one of the highest in the world.

The progress in power electronics [1], [2], [3], [4] facilitated integration of these renewable energy sources either grid or as stand-alone for small scale use. Historically, the integration was started with wind farms. When the price for photovoltaic panels became affordable, the penetration of PV became to be used more often but not necessarily at the same level of power as wind. For medium to high power the PV's are modularly used [5], [7], [8].

Many studies propose small power integration (few kW) for both wind and solar PV as hybrid stand-alone systems [6], [9], [11], [12]. Other studies added fuel cells and batteries creating the concept of multi-port system [15]-[20].

Apart from methods of integration a continuous attention was towards controlling the systems in order to maximize solar PV efficiency [7], [8], [9], [10], [11], or wind [21], [22], [23]. Stability of renewable system was also under scrutiny [2], [14].

Double or multi-port integration systems for renewable have been previously proposed [15]-[20]. The communality of all these studies proposed parallel connection of various renewable sources on a single dc bus.

In this study a double-port integration system for renewable energy sources is proposed. Figure 1 shows a small scale system of 1 kW PV array integrated together with a 1.5 kW wind generator (WG).

II. Small Scale Renewable System

The double input interface converts energy delivered by the PV array and wind generator in a comparable DC voltage when operating at nominal conditions. Due to the variable nature of wind and sun irradiation, the system must have a battery back-up. In this proposed solution the corresponding DC output voltage for each renewable source is connected in series and thus increasing the power availability at partial solar irradiation and weak wind.

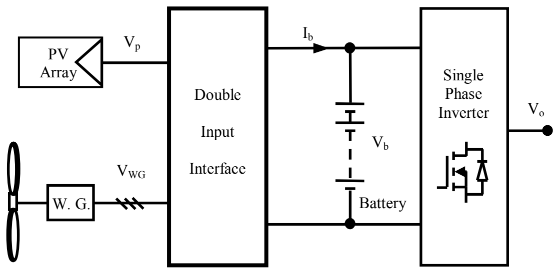

Fig.1 Double Input Renewable System

The third stage of the interface produces a charging current for the battery. During the day light, the consumption is lower than the PV can produce and the greatest part of this energy is stored into the battery. When the wind blows, the energy produced by the wind generator is also stored into battery.

Energy stored is then released for the period when there is no sun or wind.

The output of the system is a single-phase standard voltage 50 Hz PWM inverter capable of delivering 3 kW at peak demand.

A. *Photovoltaic cell model*

The equivalent model of a photovoltaic cell is shown in figure 2. The current-voltage characteristic of the cell is:

$$I = I_{ph} - I_o \left\{ exp\left[\frac{q\left(V + I \cdot R_s\right)}{nKT} \right] - 1 \right\} - \frac{V + I \cdot R_s}{R_{sh}} \qquad (1)$$

Where: I = output current; I_{ph} = photo current; I_o = saturation current of the diode; V = output voltage; q = the charge of electron; n = $\in$ [1 2] is the diode constant; K = Boltzmann constant; T = cell's temperature in Kelvin degrees; R_s = series resistance; R_{sh} = shunt resistance.

In this study, four panels rated at approximate 250 W with V_{oc} of 37 V and I_{sc} – 8.9 A. Figure 3 and 4 shows the I-V and power characteristic of one panel at standard conditions rerspectively.

For an efficient energy conversion, the panel should be operated in the MPP point.

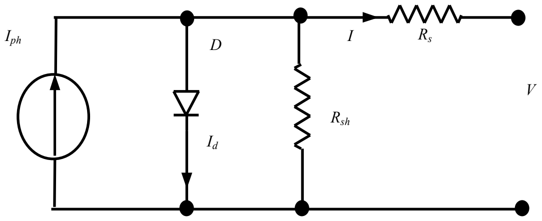

Fig.2 PV Cell's equivalent model

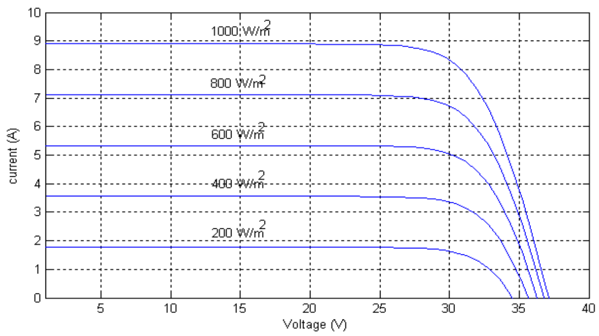

Fig.3 I/V characteristics for the panel used

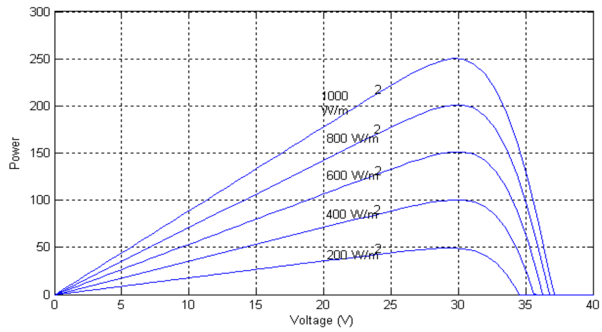

Fig.4 Power characteristics for the panel used

B. *Wind generation model*

The mechanic power produced by the wind blowing the blades is given as:

$$P_{m-W} = 0.5\rho \cdot A \cdot C_p\left(\lambda, \beta\right) \cdot v_W^3 \qquad (2)$$

Where ρ is the air density (kg/m^3), A is the turbine swept area (m^2) and v_W is the wind speed (m/s). Coefficient C_p is a dimensionless power coefficient which depends on λ and the blade pitch angle (β) [13]:

$$C_p = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 21\right) exp\left(-\frac{21}{\lambda_i}\right) + 0.0068\lambda \qquad (3)$$

With:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (4)$$

$$\lambda = \omega_m R / v_W$$

Where ω_m is the angular speed of the turbine and R is the radius of the turbine/blades.

Then, the electromagnetic torque (T_{em}) of the generator can be written as:

$$T_{m-W} - T_{em} = J\frac{d\omega_m}{dt} + B\omega_m$$
$$T_{em} = \frac{3EI}{2\omega_m} = \frac{3p\Psi}{4} I \qquad (5)$$

Where J is total inertia, B is the effective friction coefficient, p is the number of poles, Ψ is the flux linkage, E is the amplitude of the emf and I is the amplitude of the generator output current.

Then the wind turbine maximum power for different wind speeds (see figure 5) is going to be matched by electric load connected to the generator.

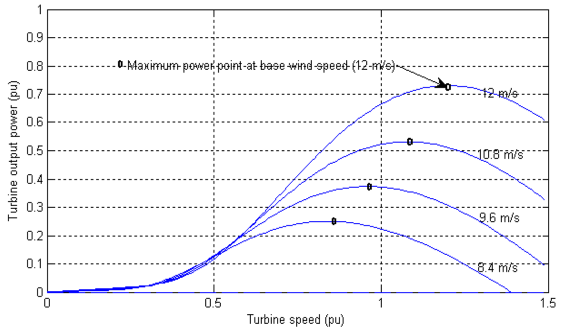

Fig.4 Turbine's power characteristics

III. DOUBLE-PORT INTERFACE

The interface proposed by this study as shown in figure 6 has two input stages to connect photovoltaic arrays and wind generation.

The first stage is a boost converter (L_1, S_1, D_1 and C1) which transfer the solar PV energy into a positive voltage source (V_1). The operation of the switch S_1 is design to adjust the inductor current (I_{L1}) as such to track the maximum power point (MPP) of the PV array. But following the MPP, the output voltage V_1 is going to vary depending on characteristics of solar cells and solar irradiation.

The second stage takes the output of the three-phase wind generator, rectifies it through $D_3 \ldots D_8$ and then the buck-boost converter (S_2, L_2, D_9, C_2) regulates the current (I_{L2}) as such to match the maximum power point of wind turbine.

The output voltage of this second stage (V_2) is negative in reference to the floating ground (FG) and can be naturally added with the output of the first stage (V_1) and thus a new voltage source (V_3) is created.

The diodes D_2 and D_{10} are used to facilitate the current flow when either solar PV output or wind output is null.

Then, (S_3, D_{11}, L_3, C_o) regulates the charging current (I_{ch}) for the battery (V_b).

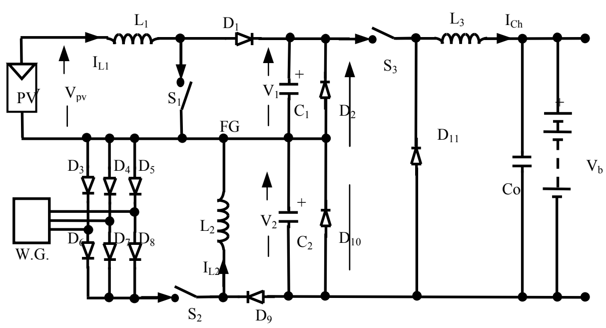

Fig.6 Double Input Interface

IV. CONTROL STRATEGY

The main purpose of the proposed system is to harvest energy from renewable sources in an efficient way. Hence the control strategy is towards each input converter to match the maximum power point for the corresponding source.

A. PV Input Control

For this application a simple PI regulator (figure 7) has been used for controlling the input current $I_{pv} = I_{L1}$.

The initial set point (δ_1) for switch S_1 and value for L_1 are chosen to satisfy the maximum power point corresponding with standard solar irradiation of 1000 W/m^2. One other parameter considered is panel temperature (T_{pv}); because the performances of photovoltaic cells depend on temperature.

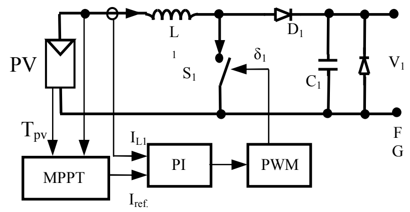

Fig.7 Control for solar PV MPPT

B. Wind Input Control

Figure 8 shows the schematic for the control strategy. In order the turbine to operate efficiently, the electrical load of the generator should match mechanic power at MPP. Usually, the generator is a permanent magnet synchronous type and frequency of the three-phase output voltage is directly proportional with the wind turbine speed. Hence, the information needed to determine the maximum power point is taken from the output of the wind generator. One easy method to find the optimal load (and turbine speed) corresponding to that wind speed (v_W), for maximum power point is using a look-up table which has been previously determined and stored [22].

Same as before, the choice of inductor L_2 and initial duty cycle δ_2 are taken to match the standard output at base wind speed.

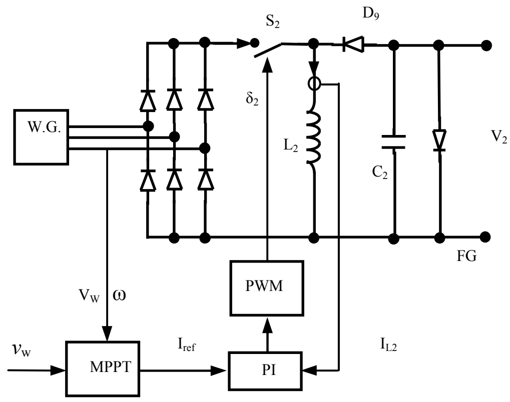

Fig.8 Control for wind generator MPPT

C. Output Regulation

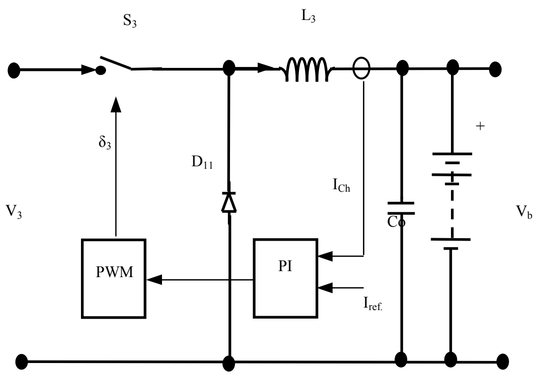

Fig.9 Control for output/charging current

The regulation of the output/charging current for the battery is done using the same type of PI controller. The reference current depends on choice of battery and its capacity in Ah.

The value of L_3 and the range of duty cycle δ_3 for S_3 depend on the range of variation of input voltage V_3. The switching should stop when the input conditions for solar PV and wind generation combined do not produce a voltage V_3 higher than battery voltage (V_b).

V. SIMULATION VALIDATION

To validate the double input interface, a simulation model has been built into the Matlab/Simulink platform. For the solar PV input a set of four panels with V_{oc} = 37 V, I_{sc} = 8.9 A rated 250 W each has been used. The combination gives the overall parameters of V_{oc} = 74 V and I_{sc} = 17.8 A.

For wind generator the parameters used are: 1.5 kW with an output three-phase voltage of 32 V_{rms} which after ac-to dc conversion becomes 72.2 V_{dc}. Figure 10 shows the DC output voltage at different wind speeds of the wind generator.

During the simulations the interface was loaded with a 2.5 kW load.

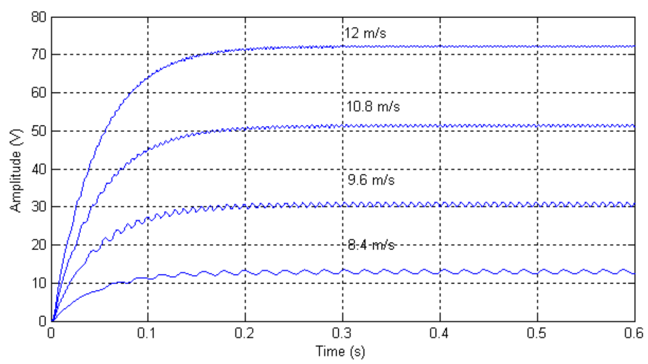

Fig.10 Wind generator dc output for different wind speed

The purpose of this validation is to proof independency of each of the two input stages, that their operation does not interfere one into each other.

Figure 11 shows the output voltages of the double input interface for both sources at nominal condition 1000W/m^2 and 12 m/s, where VDC = V_3, V_{pvconv} = V_1 and $V_{windconv}$ = - V_2.

In the following figures 12-15 are shown interface voltages for different situations from nominal (1000W/m^2 and 12 m/s) to partial conditions.

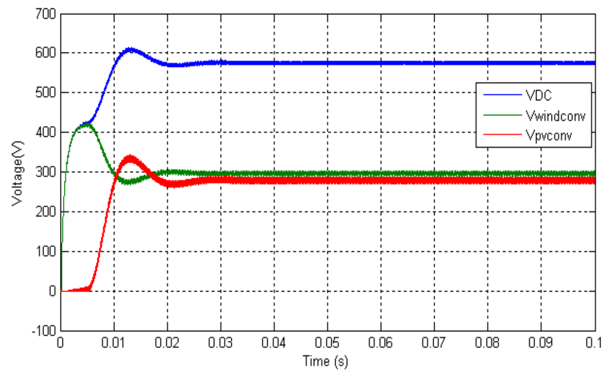

Fig.11 Voltages for nominal input conditions

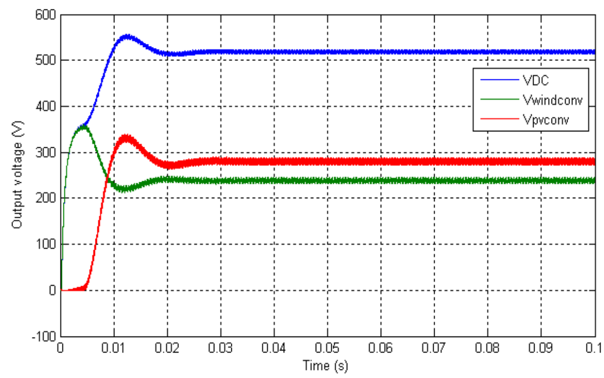

Fig.12 Interface voltages for 10.8 m/s and 1000W/m^2

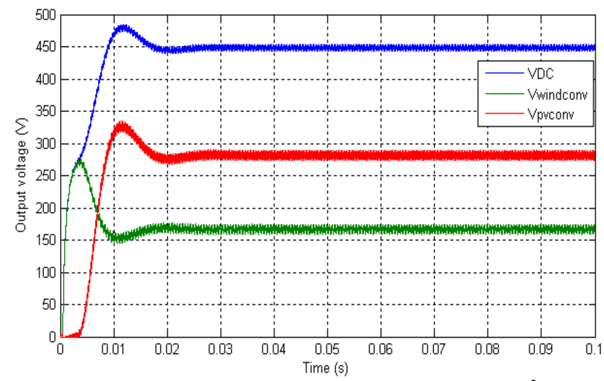

Fig.13 Interface voltages for 9.6 m/s and 1000W/m^2

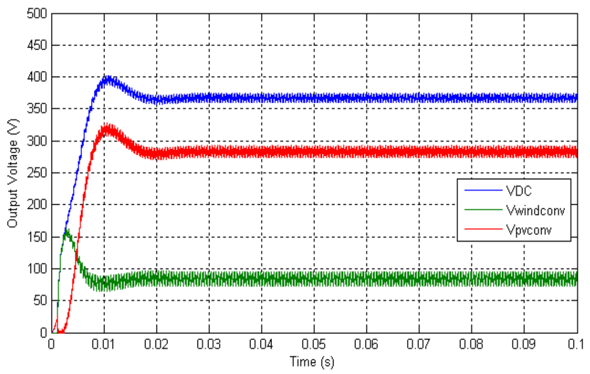

Fig.14 Interface voltages for 8.4 m/s and 1000W/m^2

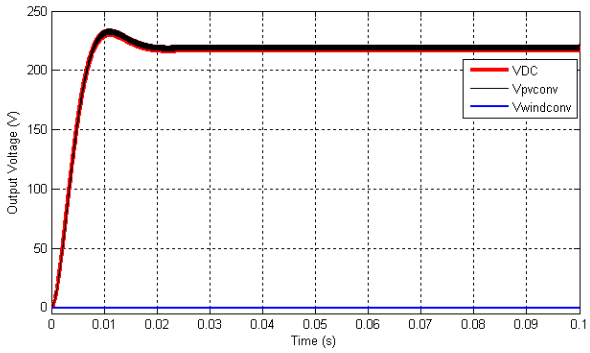

Fig.15 Interface voltages for 0 m/s and 200W/m^2

From the analysis of the above results it can be seen that each input converter function without influencing each other. A wide range of available output voltage of the double-port interface from approximately 70 V to 580 V could be estimated. According to this estimation, the characteristics of the backup battery could be chosen.

VI. Conclusion

In this paper a double-port interface has been presented. The specific of this interface consist on naturally series connection of the outputs of the two different dc/dc converter. The system is stable and there is no interference between the two input converters.

Using the data for a 1 kW PV system and 1.5 kW wind generator, the simulation results shown and extended power capability even for partial operating conditions and thus greater energy stored. Hence, this system is recommended for small scale stand-alone renewable energy system.

References

[1] S.A. Papathanassiou, G.A. Vukas and M.P. Papadopoulos, USE OF POWER ELECTRONICS CONVERTERS IN WIND AND PHOTOVOLTAIC GENERATORS, *Proceedings of IEEE International Symposium on Industrial Electronics*, July, 1995

[2] K.C Kalaistakis and G.J. Vachtsevanos, ON THE CONTROL AND STABILITY OF GRID CONNECTED PHOTOVOLTEAIC SOURCES, *IEEE Transaction on Energy Conversion*, Vol. EC-2, No. 4, Dec. 1987, pp. 556-562

[3] F. Blaabjerg, Zhe Che and S.B. Kjaer, Power Electronics as Efficient Interface in Dispersed Power Generation Systems, *IEEE Transaction on Power Electronics*, Vol. 19, No. 5, Sept. 2004, pp. 1184-1194

[4] J.M. Carrasco, L.G. Franquelo, J.T. Bialasiewicz, E. Galvan, R.C. Portillo Guisado, M.A. Partin Prats, J.I. Leon and M. Moreno-Alfonso, Power-Electronics Systems for Grid Integration of Renewable Energy Sources: A survey, *IEEE Transaction on Industrial Electronics*, Vol. 53, No. 4, Aug. 2006, pp. 1002-1016

[5] Z. Liang, R. Guo. J. Li and A.Q. Huang, A High-Efficiency PV Module-Integrated DC/DC Converter for PV Energy Harvest in FREEDM Systems, *IEEE Transaction on Power Electronics*, Vol. 26, No. 3, March 2011, pp. 897-909

[6] R. Bilinton and R. Karki, Capacity Expansion of Small Isolated Power Systems Using PV and Wind Energy, *IEEE Transaction on Power Systems*, Vol. 16, No. 4, Nov. 2001, pp. 892-897

[7] K. Sun, Li Zang, Yun Xing and J.M. Guerrero, A Distributed Control Strategy Based on DC Bus Signaling for Modular Photovoltaic Generation Systems With Battery Energy Storage, *IEEE Transaction on Power Electronics*, Vol. 19, No. 26, Oct. 2011, pp. 3032-3045

[8] H.-J. Chin, Y.-K. Lo, C.-J. Yao, T.-P. Lee, J.-M. Wang and J.-X. Lee, A Modular Self-Controlled Photovoltaic Charger With InterIntegrated Circuit (I^{2}C) Interface, *IEEE Transaction on Energy Conversion*, Vol. 26, No. 1, March 2011, pp. 281-289

[9] I.H. Altas and A.M. Sharaf, A NOVEL ON-LINE MPP ALGORITHM FOR PV ARRAYS, *IEEE Transaction on Energy Conversion*, Vol. 11, No. 4, Dec. 1996, pp. 748-754

[10] S.-K. Kim, E.-S. Kim and J.-B. Ahn, Modeling and Control of a Grid-Connected Wind/PV Hybrid Generation System, *IEEE Conference on Transmission and Distribution*, May 2006, pp. 1202-1207

[11] A.M. Sharaf and M.A.H. El-Sayed, A Novel Hybrid Wind-PV Micro Co-Generation Energy Scheme for Village Electricity, *IEEE Electric Machines and Drives Conferences*, May 2009, pp. 1244-1249

[12] S.J. Park, B.B. Kang, J.P. Yoon, I.S. Cha and J.Y. Lim, A Study on the Stand-Alone Operating or Photovoltaic/Wind Power Hybrid Generation System, 35th *Annual IEEE Power Electronics Specialists Conference*, June 2004, pp. 2095-2099

[13] Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems," John Wiley & Sons Ltd, 1998

[14] E. Serban and H. Serban, A Control Strategy for a Distributed Power Generation Microgrid Application With Voltage and Current-Controlled Source Converter, *IEEE Transaction on Power Electronics*, Vol. 25, No. 12, Dec. 2010, pp. 2981-2993

[15] D.B. Nelson, M.H. Nehrir and C. Wang, Unit Sizing of Stand-Alone Hybrid Wind/PV/Fuel Cell Power Generation Systems, Power Engineering Society General Meeting, June 2005,

[16] F. Nejabatkhah, S. Danyali, S.H. Hosseini, M. Sabahi and S. M. Niapour, Modeling and Control of a New Three-Input DC/DC Boost Converter for Hybrid PV/FC/Battery Power System, *IEEE*

Transaction on Power Electronics, Vol. 27, No. 5, May 2012, pp. 2309-2324

[17] Z. Qian, O.Abdel-Rahman, C. Hamilton, M. Batarseh and I. Batarseh, An Integrated Four-Port Converter for Compact and Efficient Hybrid Power Systems, *IEEE Proceedings for International Symposium on Circuits and Systems*, June 2010, pp. 2307-2210

[18] S. Kumaravel and S. Ashok, Design and Analysis of Multiple Input Power Conditioner for Solar PV/Wind Hybrid Energy System, IEEE TENCON Conference, Nov. 2011, pp.883-887

[19] W. Jiang and B. Fahimi, Multiport Power Electronic Interface – Concept, Modeling and Design, *IEEE Transaction on Power Electronics*, Vol. 26, No. 7, July 2011, pp. 1890-1900

[20] J.J. Nedumgatt, K.B. Jaykrisham, S. Umashankar, D. Vijayakumar and D.P. Kothari, Perturb and Observe MPPT Algorithm for Solar PV System – Modeling and Simulation, *Annual IEEE India Conference* (*INDICON*), Dec. 2011

[21] Y.-L. Juan, An Integrated-Controlled AC/DC Interface for Microscale Wind Power Generation Systems, *IEEE Transaction on Power Electronics*, Vol. 26, No. 5, May 2011, pp. 1377-1384

[22] G.D. Moor and H.J. Beukes, Maximum Power Point Trackers for Wind Turbines, 35th *Annual IEEE Power Electronics Specialists Conference*, June 2004, pp. 2095-2099

[23] Z. Simic, M. B. Vrhovcak and D. Sljivac, Small Wind Turbine Power Curve Comparison, *IEEE AFRICON*, Sept. 2009

[24] F.Y.S. Eddy and H.B. Gooi, Multi-Agent System for Optimization of Microgrids, 8th *International Conference on Power Electronics – ECCE Asia*, June 2011, pp.2374-2381