Efficiency Analysis of Stand Alone Wind/Photovoltaic Hybrid Plant Architectures

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***Abstract*—A procedure to compare the performance of Wind/Photovoltaic hybrid plants owning the same PV cell array and wind turbine, but different internal configurations is presented in this paper. The selection of the optimal internal configuration for a hybrid generation plant from renewable energies is a complex task and no widely accepted design tools are today available to compare the features of different possible architectures for a given combination of solar irradiation, wind speed and load profiles. To do this a procedure is proposed based on the evaluation of four performance indexes, namely: the global efficiency, the efficiency in transferring energy from RES to BSS, the efficiency in transferring energy from BSS to load and the fraction of useful renewable energy. The paper is mainly focused on low power hybrid Wind/Photovoltaic plants for distributed generation, however, the proposed procedure may also be adapted to high power systems**

***Index Terms*-- Hybrid system, PhotoVoltaic Generator (PVG), Wind Energy Generator (WEG), Performance indexes.**

I. Introduction

Electrical energy generation plants from renewable sources are rapidly spreading throughout the world due to a growing interest in environmental issues.

Small size photovoltaic generators (PVG) and wind energy generators (WEG) are today widely used as an alternative to conventional power plants to produce energy in remote areas that cannot be connected, for economical or technical reasons, to a main utility grid [1]. However, both photovoltaic arrays and wind turbines working in island mode cannot ensure the minimum level of power continuity required to fulfill the requirements of home or business users, due to the intermittent nature of wind speed and solar irradiation [2]. Hybrid Wind/Photovoltaic generators (HWPVG) have been then proposed to solve such a problem, taking advantage of the overlap of the availability of sun and wind power. Moreover, the addition of a Battery Storage System (BSS) makes possible to supply the load even if the total input primary power is lower than the demand. Energy storage systems play an important role in HWPV plants, providing the ground for mid term reserve energy storage as well as for quick response operations as load following or peak shaving.

The basic elements of a stand-alone HWPV with BSS can be connected together according to different approaches in order to provide the means to exchange energy, such as: DC-coupling, AC-coupling, or even more sophisticated multiple bus coupling. Therefore, a problem rises consisting in how to find the optimum internal structure configuration, considering that it significantly affects the efficiency and performance of the plant and that no widely accepted solutions emerged in the past [3,4,5].Moreover, no suitable design tools have been developed to compare different candidate structures, still leaving the selection of the internal structure of stand-alone hybrid plants to the skill and the experience of the designer.

Some attempts to solve such a problem have been presented in the past, where the optimum one among a set of candidate structures is detected evaluating the Loss of Power Supply Probability index (LPSP) [6,7,8] for standalone plants, and the Loss of Produced Power Probability index (LPPP) for grid connected plants [9].In this paper a more effective approach is proposed for stand-alone plants, taking into account specific control strategies, real solar radiation, wind speed and load time diagrams, as well as, the efficiency of each power converter. To do this suitable dynamic models have been carried out through MatLab/Simulink/ SimPowSys^{TM}.

II. Bus Voltage Configurations

In this paper five possible internal structure configurations have been considered to build a stand-alone HWPV generator with BSS. Details about parameters of the main subsystems of this plant are given in Table I.

TABLE I
PVG AND WEG MAIN DATA

PVG	
Module model	Solyndra® - SL001-157
Module unit	157Wp at STC
Module open circuit voltage	92.5 V
Module number	3 × 4 = 12
Power rating	1.88kWp
WEG	
Model	TN-1.5 Nozzi Nord
Rated power	1.5kW
Cut in/Cut out speed	4m/s &20m/s
Generator type and ratings	1.5kW PMSG @ 50 Hz

The five considered internal configurations are: high voltage DC bus (HVDC), low voltage DC bus (LVDC), High voltage AC bus (HVAC), high voltage AC rectified bus (HVAC rect.) and double bus (LV/HVDC). The two power generators and the BSS are supposed to be regulated by independent control systems. The two managing the operation of the PV array and the wind turbine also accounting for the Maximum Power Point Tracking (MPPT) [10].

Suitable mathematical models of all the elements of the system have been previously modeled [11, 12] and a detailed description of these models is beyond the objective of this paper.

A. HVDC bus configuration

In this configuration, the power generated from the two sources is delivered to the load through a high voltage DC bus. Therefore, such a configuration requires the installation of an ad hoc DC operated network. Fig. 1 shows a schematic of a stand-alone HWPV generator with BSS featuring a HVDC bus configuration. As shown in table II, the amount of conversion steps required to deliver power to the BSS or to the grid is relatively low, thus reducing the conversion losses and the cost.

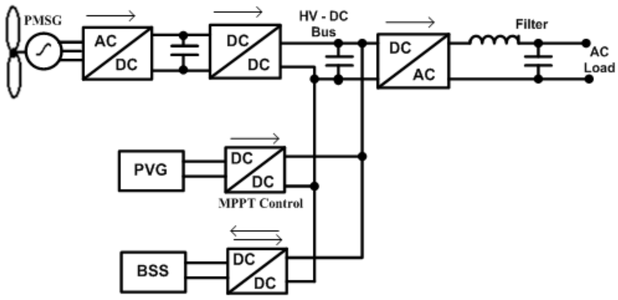


Fig. 1.Schematic of HVDC bus hybrid system

B. LVDC bus configuration

According to the scheme shown in Fig. 2 the generated power is delivered to the load via a low voltage DC bus (36-100)V. In a preliminary simulation study, the low DC bus voltage is rated at 96V. In this configuration, the BSS is attached directly to the low voltage DC bus; this allows to store energy without conversion losses.

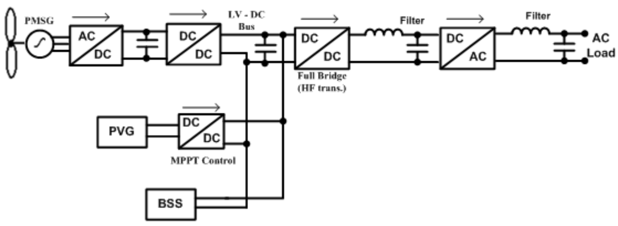


Fig. 2. Schematic of LVDC bus hybrid system

C. HVAC bus configuration

Fig. 3 shows a schematic diagram of a traditional stand-alone HWPV plant with BSS. The generated power is delivered to the load through an AC bus.

The great advantage of this configuration is that it can use existing AC infrastructures and facilities. This allows an easy and inexpensive allocation of the elements of the plant, even at considerable distance. Moreover, the possibility of achieving 'plug and play' modules designed to be directly connected to the AC single phase home network is an interesting perspective.

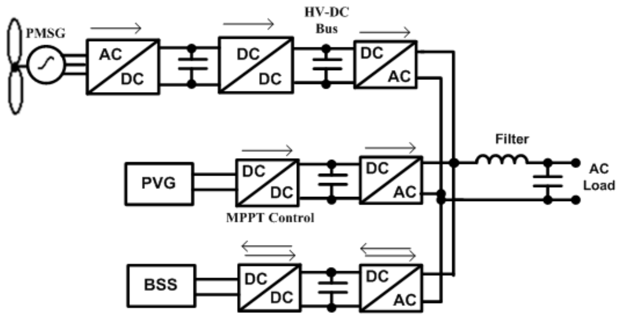


Fig. 3. Schematic of HVAC bus hybrid system

D. HVAC rectified bus configuration

Fig. 4 shows the schematic of a stand-alone HWPV with BSS, where the generated power is delivered to the load via an AC_{rect}/AC converter. Each generator is equipped to directly provide power to a bus featuring a voltage with an AC rectified waveform. According to such an approach each inverter operates in square wave mode, with a high efficiency.

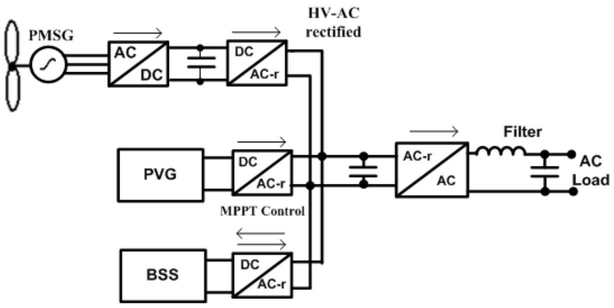


Fig. 4.Schematic of HVAC-Recthybrid system

E. LV/HV DC bus configuration (double bus)

Fig. 5 shows the schematic diagram of a plant featuring a sophisticated double DC bus configuration, where a low voltage DC bus is used to store energy, while a high voltage DC bus is exploited to deliver power to the grid.

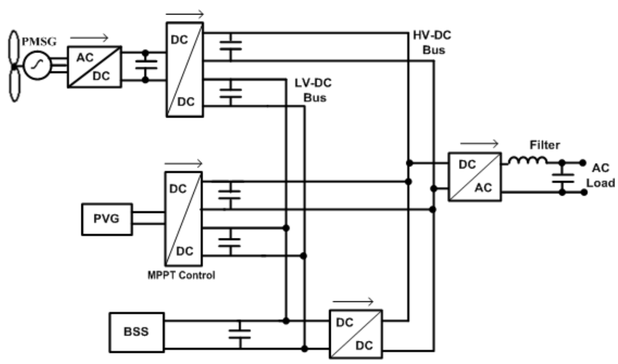


Fig. 5.Schematic of LV/HV-DC bus hybrid system

TABLE II
AMOUNT OF REQUIRED CONVERSION STEPS

	HVAC	LVDC	HVDC	$HVAC_{rect}$	LV/HVDC
PV→Grid	2	3	2	1+1*	2
WT→Grid	2	3	3	2+1*	2
PV→ESS	3	1	2	2	1
WT→ESS	3	1	3	3	1
PV→ESS→Grid	5	3	4	3+1*	3
WT→ESS→Grid	5	3	5	4+1*	3
1* = unfolder mode voltage inversion					

III. The Proposed Approach

A conversion steps analysis, as that accomplished in Tab 2, gives only a first quick comparison among the above considered configurations, however, it is insufficient to effectively detect of the most advantageous configuration for a specific plant design.

A more sophisticated comparison can be accomplished on the basis of four performance indexes, namely: global efficiency, efficiency in transferring energy from RES to BSS, efficiency in transferring energy from BSS to load and fraction of useful renewable energy, as defined in the following.

A. Global Efficiency Index

The global efficiency (η_{global}) of an HWPV power plant is given by Eq. (1):

$$\eta_{global} = \frac{E_{out}}{E_{in}} \quad (1)$$

$$E_{conv.\_losses} = E_{in} - E_{out} \quad (2)$$

$$\eta_{global} = 1 - \frac{E_{conv.\_losses}}{E_{in}} \quad (3)$$

Where $E_{conv.\_losses}$ are the total energy conversion losses, E_{in} is the input energy from PVG, WEG and BSS.

According to the proposed approach, the global efficiency of a given configuration is computed according to specific daily input weather and load profiles through a procedure taking into account the efficiency of single components, whose flow diagram is drawn in Fig. 6.

A day of operations is divided into 24 intervals each one hour long. The global efficiency of the considered plant in each time interval is computed starting by computation of the energy captured by the PV cell set and the wind turbine and the power delivered to the load according to the considered load, wind speed and solar radiation diagrams.

Operating points of the power converters are then determined in terms of input power, through the mathematical model of the plant.

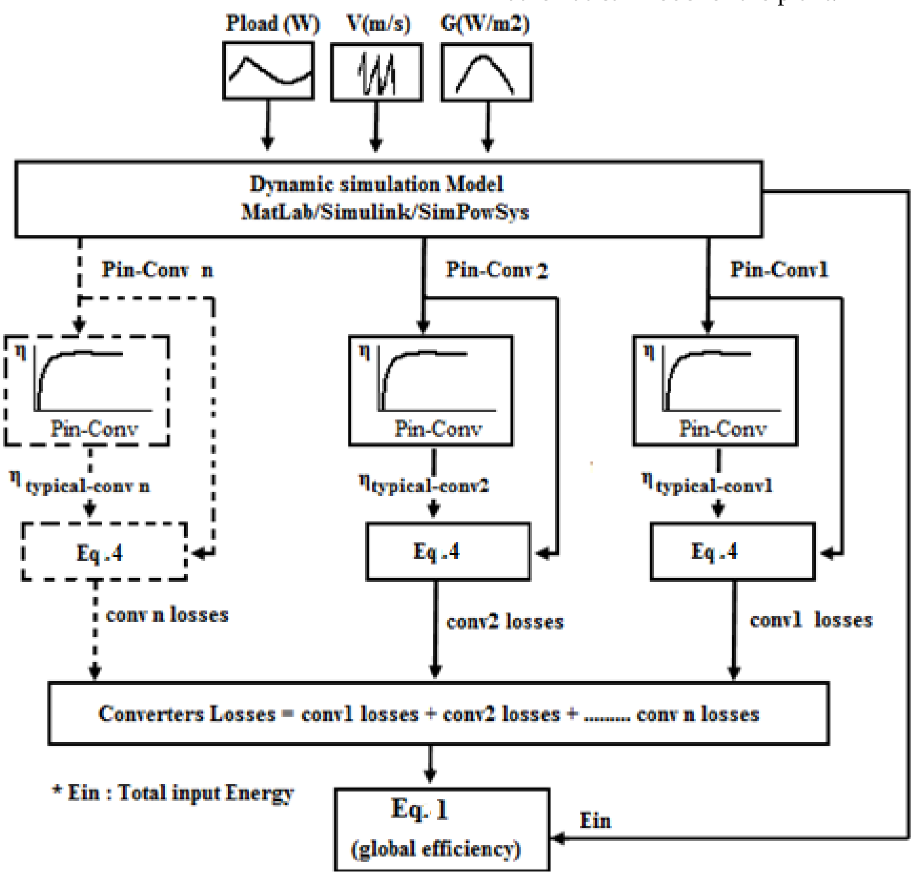


Fig. 10.Flow chart of global efficiency computation.

Energy conversion losses of each power converter in the considered interval are computed looking at the typical efficiency curve of the specific power converter using Eq. (4).

$$E_{conv-losses\ n} = P_{in-conv\ n}\left(1-\eta_{typical-conv}\right) * \Delta t \quad (4)$$

where $P_{in-conv n}$ is the n converter input power and $\eta_{typical-conv\ n}$ is its typical efficiency at $P_{in-conv}$, as obtained from the diagrams of Figs. 7-10.

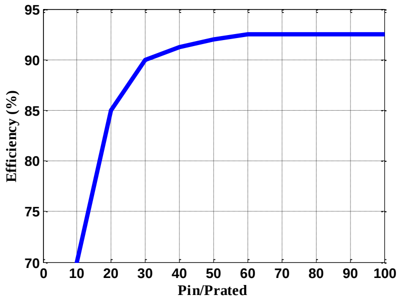


Fig.7. Typical efficiency of a 2kW DC/DC converter

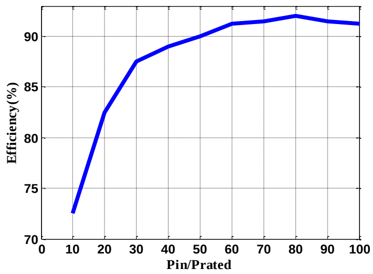


Fig. 8. Typical efficiency of a 2kW rectifier

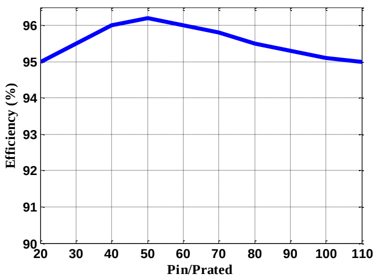
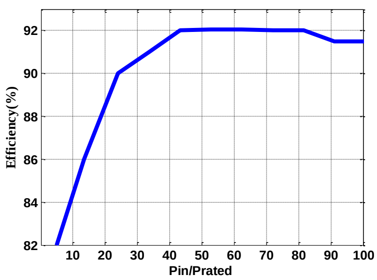


Fig. 9.Typical efficiency of a 5kW PWM inverter



Fog. 10. Typical efficiency of a 5kW full bridge DC/DC converter

Total converters losses, along a day can be then easily computed by adding the power losses computed for each converter along the 24 intervals to obtain the global efficiency as defined in Eq. (3).

The average power demand profile for a home load in Italy in the cold season, the average wind speed, solar irradiance and air temperature in a typical day of December in the town of Messina, Italy, are considered as an example.

Fig. 11 shows the global efficiencies featured by the five configurations in this specific case.

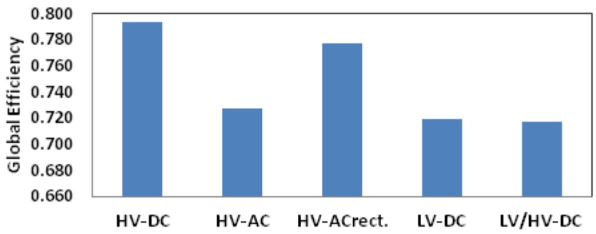


Fig.11. Global efficiency of different bus voltage configurations

As it is possible to observe, the HVDC bus configuration obtains the highest global efficiency and $HVAC_{rect}$. bus configuration comes in the next.

The global efficiency doesn't depend only on the number of conversion steps as generally known. In fact other conditions may play significant roles in determining the effectiveness of energy flow from different energy sources and load such as the control strategy and the efficiency of power converters.

B. *Efficiency in transferring energy from RES to BSS*

The efficiency in transferring energy from RES to BSS (ηRES-->BSS) is an important index in evaluating the whole plant efficiency. It is obtained by simulations on the basis of the typical efficiency curves of power converters.

$$\eta RES \rightarrow BSS = \frac{E_{RE}}{E_{BSS}} \quad (5)$$

Where E_{RE} is the amount useful energy from renewable energy sources to batteries E_{BSS}. A comparison of the five configurations in terms of such index is shown in Fig. 12.In this case HVDC, LVDC and LV/HV-DC configurations reach the highest levels of efficiency

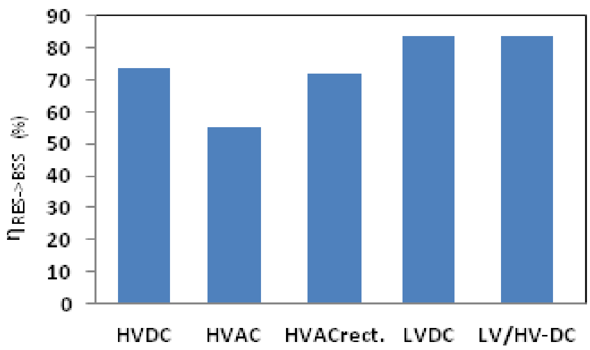


Fig.12. Average RES-->BSS efficiencyof thefive configurations.

C. Efficiency of energy delivered from BSS to load

Another important index to analyze the efficiency of an HWPVG is the efficiency in transferring energy from BSS to load (ηBSS-->Load).
It can be computed through the mathematical model of the plant.

$$\eta BSS \rightarrow LOAD = \frac{E_L}{E_{BSS}} \qquad (6)$$

Where E_L is the amount of energy load supplied by batteries E_{BSS}. According to Fig.13, good results are obtained by all the considered configurations.
However HVDC, HVAC and LV/HVDC configuration are the best.

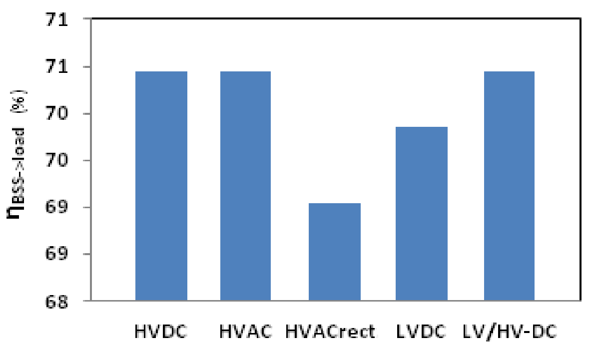


Fig.13. Average η_{BSS}-->Load index of five bus voltage configurations

D. Fraction of useful renewable energy performance index

The solar fraction is defined as the portion of energy consumed by the end user that is ultimately provided by the photovoltaic array [12].

This concept has been adapted to fit the case of a hybrid system including a wind turbine and a BSS. Therefore the useful renewable energy fraction (RE-Fraction) is defined as the fraction of the end-use energy supplied by PVG and WEG. It is computed as shown in Eq(7).

$$RE - Fraction = UsefulRE/EL$$
$$= (InputRE - E_{conv.\_losses})/EL \qquad (7)$$

Where EL is the energy supplied to the load and RE is the total captured renewable energy.
This performance index is useful in determining how well the system acts is managing the available renewable energy. Fig. 14 shows RE-Fraction achieved by the considered five configurations. The maximum RE-Fraction is obtained by the HV-DC bus configuration and the HV-AC rect. bus configuration comes in the next.
The LV-DC and LV/HV-DC have similar scores.

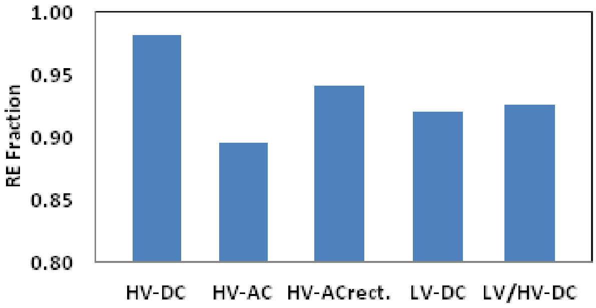


Fig.14. RE-Fraction of different bus voltage configurations

IV. Analysis of Obtained Results

On the basis of obtained results it is found that, at least for the specific case study considered:

- The HVDC bus configuration features the highest global efficiency 79.3%, while the HVAC-rect. configuration is comparable to the HVDC configuration scoring 77.7%. Finally, HVAC, LVDC and LV/HV-DC configurations show lower levels of efficiency: 72.7%, 71.9%, 71.7% respectively.
- The LVDC and LV/HV-DC configurations are particularly efficient in storing energy (ηRES-->BSS), while HVAC is the less efficient. The HVDC and $HVAC_{rect}$. bus configurations are in between.
- In case of energy delivery to load from BSS (ηBSS-->Load), all configurations obtain a quite similar efficiency.
- The HVDC bus configuration draws the maximum RE-Fraction, which indicates the best utilization of available renewable energy sources. The HVAC-rect. bus configuration is 4.2% worse than HVDC, while the HVAC, LVDC and LV/HV-DC are respectively 8.3%, 6.3% and 5.3% less efficient than HVDC.

Based on these comings the HVDC bus configuration appears the most effective configuration as:

- HVDC obtains the highest global efficiency and fraction of useful renewable energy performance indexes.
- HVDC obtains the highest value of ηBSS-->load index (efficiency of energy delivered from BSS).
- HVDC is in the middle between the best and worst result in terms of ηRES-->BSS index (efficiency of energy delivered from RES to BSS).

V. Conclusion

In this paper an new approach is proposed to identify the most advantageous internal configuration for a HWPVG encompassing PVG, WEG and BSS, taking into account real solar radiation, wind speed and load time diagrams, as well as, the efficiency of power converters. To do this a suitable procedure has been developed based on the evaluation of four performance indexes, namely: the global efficiency, the efficiency in transferring energy from RES to BSS, the efficiency in transferring energy from BSS to load and the fraction of useful renewable energy. Five different internal architectures were compared in a case study, namely: high voltage DC bus (HVDC), low voltage DC bus (LVDC), High voltage AC bus (HVAC), high voltage AC rectified bus (HVAC rect.) and double bus (LV/HVDC). According to the obtained results the HVDC bus configuration appears as the most effective, as it reach the highest levels of global efficiency, fraction of useful renewable energy and efficiency in transferring the energy stored in the BSS to the grid, while achieving a of efficiency in transferring energy from RES to BSS.

Although obtained results heavily depends from the particular case studied, the proposed procedure is general and can be applied to plants featuring any internal configuration and any size.

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