Power Maximization of a PV-Wind HRES via DC-link Voltage Boosting

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Abstract. This paper describes a method for the optimization of a Hybrid Renewable Energy System applied to a low power Photovoltaic-Wind plant. This approach exploits the DC link with a voltage higher than the correspondent value of the batteries, thanks to a suitable DC/DC converter. The goodness of the methodology is firstly proved by means of a novel graphical technique and then verified through numerical simulations. The results are discussed and show that, adopting the proposed technique, a significant increase of the generated power and of the annual energy produced can be achieved.

Key Words: HRES, PV-wind, optimization, maximum power, DC/DC converter, voltage boost.

1. Introduction

As it is known, a Hybrid Renewable Energy System (HRES) is a system aimed at the production and utilization of the electrical energy coming from more than one source, provided that at least one of them is renewable. Such a system often includes some kind of storage in order to satisfy the demand during the periods in which the renewable sources are not available and to decrease the time shift between the peak load and the maximum power produced.

Actually low power HRES are of great interest in the market due to the wide possibility of utilization, hence their optimization is particularly needed [1]-[4]. As a matter of fact, hybrid systems with PV/Wind energy sources and diesel generator [5]-[6], with or without batteries, are used regularly to satisfy the energy requirements of remote areas in a reliable and cost effective way [7]. They are used to produce fresh water through desalination as well and there are also examples of microgrids with a PV generator and a fuel cell in cogeneration, in order to supply the loads seasonally.

In a conventional low power stand-alone renewable system, the storage device, e.g. the battery, is connected directly to the DC-link, together with the charge regulator(s) of the generator(s) and the input stage of the inverter. These charge regulators are often DC/DC converters controlled with PWM (Pulse Width Modulation) technique.

Such a realization is cheap but has the constraint that the DC-link is connected to the batteries; as a consequence its voltage can be different from the voltage corresponding to the maximum power point (MPP) of the renewable source, which therefore cannot be optimally exploited. This problem is deeply described in section 2 where a graphical method of analysis is proposed. Section 3 contains the system design and in section 4 several scenarios are simulated with Simulink and PLECS. The results are synthesized in section 5 and finally in section 6 conclusions are given. The local conclusions within a section are highlighted with italic font.

2. Discussion

The external characteristic of the different renewable sources, i.e. the plot of the relationship between current and voltage, is not always linear, like in a P.M. brushless wind turbine (WT). Photovoltaic generators and fuel cells exhibit a non linear characteristic, with a neat "knee". For a linear generator the maximum power point (MPP) is the middle point of the characteristic; for a non linear generator, instead, the MPP is coincident with the knee.

When the operating conditions change, the characteristic of a generator is modified. For a non linear generator the open circuit point stays almost constant, while the short circuit point varies significantly. For a linear source, instead, these two points vary simultaneously so that the different characteristics obtained are parallel to each other. As a consequence, the DC-link voltage is very close to the battery e.m.f. and, thus, far from the MPP voltage of the generator(s). Hence, the power production can be maximized if the DC-link voltage is properly boosted.

In the following it is proved that when a renewable system employs PWM converters (e.g. a charge regulator in a stand-alone system or a MPPT circuit in a grid-connected one) the maximum power deliverable by each generator is lower that the theoretical value. Furthermore, it is shown that the power produced depends on the voltage level on the DC-link; hence it should be kept as high as possible, yet respecting some limits. The above mentioned ideas are demonstrated with a novel graphical construction on the (I vs. V) plane, which in addition allows to forecast the behaviour of the system.

The proposed graphical analysis shows that using the DC-link voltage as a variable, the power production can be maximized if the DC-link voltage is properly boosted. This relationship between the DC-link voltage level and the produced power extends the conclusions in [8], since the limits to the voltage increase are discussed and because hybrid systems are also considered.

2-1 Distribution of the generator current between battery and load

In order to evaluate the distribution of the generator current (e.g. for a PV generator) between the battery and a load R_L, an analysis is performed on the I-V plane by comparing the characteristic of the generator and the one of the "load and battery" set. This latter characteristic, if the battery is modelled as a voltage source, E_0, with an internal resistance R_B, is represented by line 'r' in figure 1 and it has the following equation:

$$I_{PV} = \frac{V_{PV}}{R_{BL}} - |I_{B,CC}| \quad \text{with } R_{BL} = \left(\frac{R_L \cdot R_B}{R_L + R_B}\right) \text{ and } |I_{B,CC}| = \frac{E_0}{R_B} \quad (1)$$

The characteristic of the battery alone (line 's') and the one related to the PV generator (green) are also represented. Point P' is the operating point of the generator and it has the coordinates P'=(V'_{PV}; I'_{PV}). Starting from this point, if a vertical segment is traced down to the intersection with line 's', point Q' is located. The y-coordinate of Q' gives the current supplied to the battery (I'_B), while segment P'Q' gives the current requested by the load (I'_L), according to the following relationship: $I'_{PV}=I'_B+I'_L$.

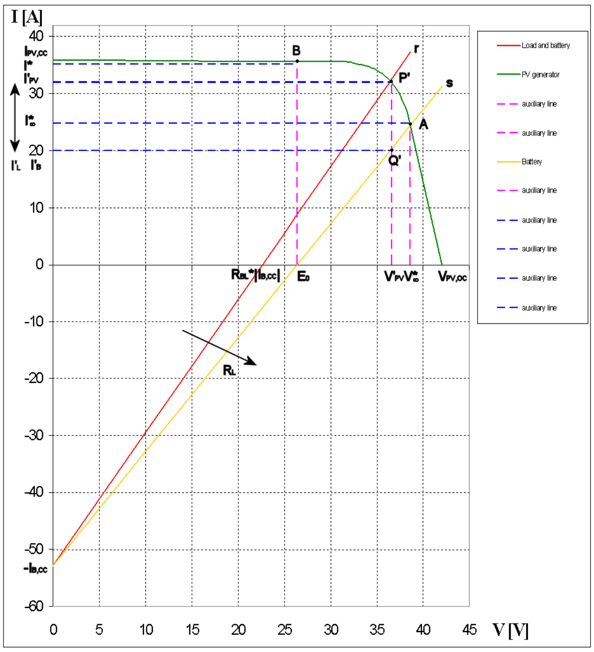

Fig. 1. Graphical construction to split the generator current between battery and load

As the load resistance increases, line 'r' moves as shown, until it becomes superimposed to line 's' when the load is disconnected. Therefore, it is clear that the operating point P' cannot move to the right of point A. Moreover I^*_∞ is the maximum charge current which can flow into the battery.

By drawing a vertical segment from point E_0 up to the intersection with the characteristic of the generator, point B can be identified. This operating point is related to the condition when no current flows into the battery. On the contrary, if the operating point moves to the left of point B, the battery will be discharged. It is worth noting that figure 1 is not in scale. As the internal resistance of the battery is very low compared to the load, line 'r' and line 's' are actually nearly vertical and almost superimposed. Hence, points P' and A are situated on the left of the MPP of the PV generator.

2-2 Systems with PWM converters

In the following the analysis of a system which employs a buck PWM converter will be discussed.

The Pulse Width Modulation (PWM) [9] is a technique which allows to regulate the average value of a voltage/current by modulating the width of a series of pulses by means of semiconductor devices which periodically open and close a circuit with defined switching period (T_s) and duty-cycle $d = \frac{t_{on}}{T_s} = \frac{t_{on}}{t_{on} + t_{off}}$.

This technique is used for example in step-down and step-up converters, supplied by an ideal voltage source E. As to the first type of converter during the conduction interval (t_{on}) power is transferred from the source to the load, while during the non conduction interval (t_{off}) no power is transferred. The voltage and current on the load will periodically vary from (V_{max}=E; I_{max}) to (0; 0).

Since these relevant excursions are generally not tolerated by the load, a filter is used in order to extract the mean value of the modulated voltage (V_M=d·E). This implies that the current on the load is not variable, but nearly constant (with a ripple superimposed) and equal to the maximum value which would have established in the circuit without the filter (I_{max}); this happens because during t_{off} the energy stored in the filter throughout t_{on} is used. It is trivial to verify that the average input power $P_M = E \cdot (d \cdot I_{\max})$ is equal to the average power at the output stage $P_M = (E \cdot d) \cdot I_{\max}$.

However, when a real source with its internal resistance R_g is connected to the converter, the input voltage during t_{on} will be lower than the e.m.f. E, for the unavoidable voltage drop: $V_{\min} = E - R_g \cdot I_{\max}$. Since during t_{off} the current is zero (and the voltage is E), it is possible to pretend that, instead of the real source, an ideal source V_{min} is connected to the circuit; therefore the mean voltage on the load is $V_M = d \cdot v_{in} = d \cdot V_{\min}$, while the average voltage at the input of the filter is $V_{M\_in} = d \cdot V_{\min} + (1-d) \cdot E$. For this reason, the product of the average values of voltage and current of the generator does not give the average output power, which is always equal to the input power, but a fictitious power:

$$P_{M\_in}=d \cdot (P_{max})=d \cdot (I_{max} \cdot V_{min}) \quad (2)$$

$$P_{M\_out}=(d \cdot V_{min}) \cdot I_{max}= d \cdot P_{max}=P_{M\_in} \quad (3)$$

$$P_{fictitious}=V_{M\_in} \cdot I_{M\_in}=(d \cdot V_{min}+(1-d) \cdot E) \cdot I_{max}= =P_{M\_in}+(1-d) \cdot E \cdot I_{max} \quad (4)$$

In conclusion, during the PWM the operating point of the generator moves from (E;0) with zero power during t_{off}, to (V_{min}; I_{max}) with maximum power (P_{max}) during t_{on}; (V_{min}; $d \cdot I_{max}$) is the average operating point of the generator as to the mean power (P_M), while (V_{M_in}, $d \cdot I_{max}$) is its average operating point as to the voltage.

Figure 2 shows the graphical analysis for both a linear and a non linear generator in a system with a PWM step-down charge regulator. The red line is the load characteristic; the vertical blue line is the DC-link voltage, which is supposed to be known. By intersecting these lines it is possible to find the point $P=(V_L; I_L)$, which is the load operating point.

The product of voltage and current on the load gives the power requested which, neglecting the losses, is equal to the average power when the converter is supplied by the generator: $P_M=P_L=V_L \cdot I_L$. Therefore, the green hyperbole which passes for point P is the locus of the operating points with power P_M.

Since the load current is the current I_{max} of the PWM, it is possible to draw the horizontal segment (orange) from point P to the characteristic of the generator (black, solid or dashed). The intersection $P_1=(V_{min}; I_{max})$ is the operating point during t_{on}, so the x-coordinate of P_1 gives V_{min}. From this value, it is possible to determine the duty-cycle: $d=\frac{V_{bus}}{V_{min}}$. The purple hyperbole which passes through point P_1 is the locus of the operating points with power $P_{max}=V_{min} \cdot I_{max}$ and it is obviously $P_M=P_{max} \cdot d$. This relationship gives an alternative way to determine the duty-cycle: $d=\frac{P_M}{P_{max}}$. It is now possible to determine the average value of the current supplied by the generator: $I_M=\frac{P_M}{V_{min}}$. Graphically it is necessary to draw the vertical line from P_1 to the hyperbole P_M; the y-coordinate of the intersection $P_2=(V_{min}, I_M)$ will give the desired value.

If the generator is linear then the coordinates of its average operating point must satisfy its characteristic equation. Therefore, it is possible to determine the average voltage by tracing the horizontal segment from P_2 to the characteristic of the generator (dashed black): the x-coordinate of the intersection $P_3=(V_M, I_M)$ will give the desired value. For a non linear generator (solid black), on the contrary, the average voltage must be evaluated according to equation (4), i.e. considering point P_3 as if it was on the line from point P_0 to P_1.

All the previuos considerations are based on the assumption that the voltage on the DC-link is actually V_{bus}. However, in order to prevent the stall of the converter, it is necessary to limit the operating range for the duty-cycle, typically to the interval [0.1; 0.9]. Therefore, the ratio of the voltages V_{bus} and V_{min} should be verified; if it does not belong to the previous interval, the system will settle on a different V_{bus}, in order to verify the previous condition. This means that the vertical blue line should be properly moved to the left or to the right, and the graphical analysis should be repeated.

A similar behaviour is exhibited also when a very high voltage set point is imposed in a system with a non linear generator, so that point P is above the non linear characteristic: the graphical construction would be impossible to do and the system would automatically decrease the voltage on the bus.

In conclusion, the operating point of the generator moves from P_0 (during t_{off}) to P_1 (during t_{on}) as the PWM is performed; P_2 is the average operating point as to the power and P_3 is the average operating point as to the voltage and current. The system is stable in all operating points (reached in a brief transient) except for some severe overload conditions. Similar considerations can be made for a system with a step-up converter, where the average operating points of the generator will be on the left of the vertical blue line.

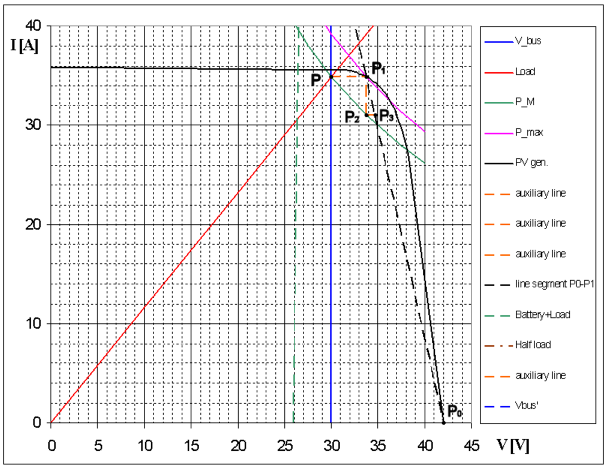

Fig. 2. Graphical analysis for a linear and a non linear generator in a system with a PWM buck charge regulator

If the graphical construction shown in figure 2 is modified so that P_1 is coincident with the MPP and $d=d_{max}$, it will represent the operating condition in which the maximum power is delivered to the load: $P_M|_{max}=d_{max} \cdot P_{MPP}$. Therefore, it is proved that the utilization of PWM converters, which are indeed necessary, doesn't allow to operate each source in its true MPP.

As to the grid-connected operation no problems arise, since the MPPT circuit will vary the apparent load in order to maximize the power. As an example, for lower values of R_L the balance could not be maintained and the voltage on the bus would decrease.

If a battery is also connected to the DC-link, instead of the red line the green dashed one should be used, which is related to the "battery and load" set. Again, point P will be too high above the PV characteristic, so the voltage on the DC-link will have to decrease to a value which is just a little higher than the e.m.f. of the battery. In this condition lower values of duty-cycle and power supplied are experienced.

Even if the load changes, the new characteristic of the "battery and load" set will be very close to the one *in figure 2, i.e. a nearly vertical line whose x-coordinate is the e.m.f. of the storage device. Therefore, for the considered system a mismatch between the generator and the battery is noticed; on the contrary, in order to maximize the generated power in a stand-alone system, the following relationship between the battery e.m.f. E (which is close to the voltage on the bus) and the V_{MPP} of the generator should be respected:*

$$E \cong V_{bus} = d_{max} \cdot V_{MPP} \quad (5)$$

yet not exceeding the maximum voltage allowed for the load (e.g. about 30 V for a 24 V nominal load).

PV generator (non linear)

As to the previous consideration, when a PV generator is used, since the MPP voltage varies slightly with the operating conditions, an optimal matching can be achieved indeed. Therefore, it is desirable that the manufacturers produce their PV modules taking into account equation (5).

Wind generator (linear)

If a wind generator is used, since the MPP voltage is very different as the operating conditions change, an optimal matching cannot be obtained, except for a small range of wind speed. Therefore, P.M. brushless wind turbine are not suited for the stand-alone operation and the producibility curves reported by the manufacturers should be referred only to the grid-connected operation, i.e. with a MPPT circuit.

Hybrid System

The graphical construction of figure 3 is based upon the consideration that the DC-link voltage is common to the outputs of the converters related to the two generators. Also it is supposed that the duty-cycles of the converters are equal; this is indeed true in a stand-alone system, where the regulators of the converters try to impose the same voltage on the DC-link, since they see the same error signal (V^*_{bus}-V_{bus}). Otherwise, with different set-points the converter with the lower one prevails and the other settles to the maximum duty-cycle. The operation of a grid-connected system, instead, will be discussed later.

Supposing that the voltage V_{bus} is known, it corresponds to a vertical line on the I-V plane (purple), and it has to be intersected with one of the characteristics of the load alone (red) or of the “battery and load” set (blue). As an example, by choosing the higher load characteristic, point P is obtained.

The length of segment AP gives the value of the current on the load, and it is the sum of two contributions from the generators; thus, it is possible to move this segment, without any rotation, so that points P and A respectively belong to the characteristics of each generator (PV: black, WT: brown). Doing so, the line segment P_1P_1’ is obtained and it can be splitted into the segments P_1B and BP_1’, which give the current supplied by each generator (I_L=I_{PV}+I_{WT}, with I_{WT} taken without sign).

Points P_1 and P_1’ are related to the operation during t_{on}, hence to the maximum value of the instantaneous power (pink and light blue, solid). They have the following coordinates: P_1=(V_{min}; I_{PVmax}) and P_1’=(V_{min}; -I_{WTmax}). The x-coordinate is the same for hypothesis and it is $V_{PVmin}=V_{WTmin}=\dfrac{V_{bus}}{d}$. Using the inverse formula it is possible to determine the duty-cycle $d=\dfrac{V_{bus}}{V_{\min}}$. Should it be d>0.9, then it will not be possible to obtain a balance with the supposed V_{bus}, so the system will settle on lower values for d and V_{bus}, and the construction will have to be repeated.

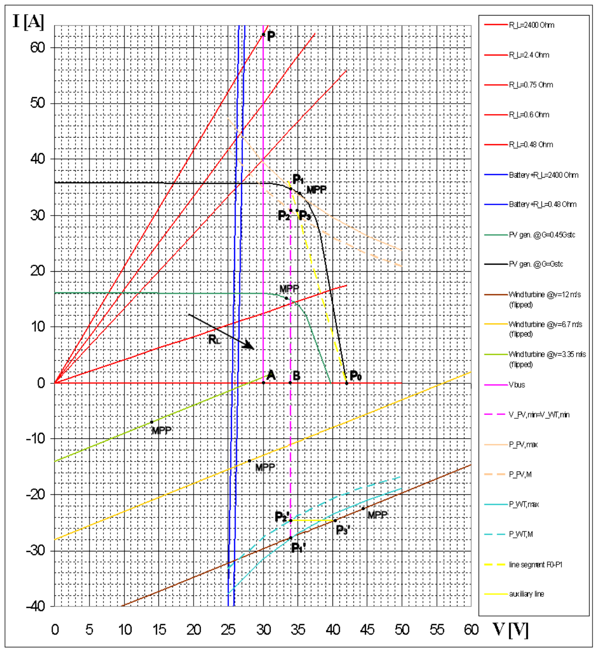

Fig. 3. Graphical analysis for a PV-wind HRES with or without a battery, with constant DC-link voltage

Having obtained d, it is possible to identify points P_2=(V_{min}; I_{PV_M}) and P_2’=(V_{min}; -I_{WT_M}) and the corresponding hyperboles (pink and light blue, dashed), which are related to the mean value of the power supplied by the two generators. Finally, as previously discussed, it is possible to obtain the average operating points of the generators (P_3 and P_3’) and specifically their x-coordinates.

If the duty-cycles are different (stand-alone operation with different set-points), starting from the situation in figure 3, the two line segments P_1B and BP_1’ will move in opposite directions while keeping points P_1 and P_1’ on the characteristic of their respective generator, until a balance is achieved: the sum of the new line segments P_1B and BP_1’ should be still equal to the total current supplied (segment AP) and the two duty-cycles should be respected. If a balance cannot be achieved by respecting the limits on d_{max} and d_{min}, the system will automatically decrease the value of V_{bus}.

It is possible to evaluate whether the operating points are close to the MPPs directly or by comparing the value of V_{bus} to both the V_{MPP}.

Therefore, as to the hybrid stand-alone operation the different characteristics of the "battery and load" set must be considered and, since they are very close to each other, a mismatch between the storage device and the generators is noticed again. However, as the operating conditions change, an optimal matching cannot be obtained for the WT, so it is convenient to realize an optimal matching with the PV generator at least. This can be accomplished by increasing the voltage of the storage device.

It is clear that the operation of the whole system is mostly influenced by the non linear generator. Furthermore, it is desirable that the maximum $V_{WT,MPP}$ is lower than the maximum $V_{PV,MPP}$; otherwise the operating point will never be close to the first voltage.

As to the hybrid grid-connected operation, instead, a specific set-point for V_{bus} is not imposed; on the contrary each MPPT circuit, independently from the others, tries to change the apparent load which is common to the outputs of the converters, in order to maximize the power supplied by its own generator.

It will be shown that the condition in which a HRES is operated at its maximum deliverable power is very close to the condition when every duty-cycle is set to d_{max} and the DC-link voltage is kept in the range between the two MPP voltages and closer to the one related to a higher power. This is true when it does not happen that one V_{MPP} doesn't belong to the characteristic of the other generator, otherwise it will be $V_{bus}=d_{max}\cdot min\{V_{PV\_MPP}; V_{WT\_MPP}\}$.

Furthermore, due to the PWM, the maximum deliverable power is lower or equal to the product of d_{max} multiplied by the sum of the maximum powers of the generators, and the deviation from this quantity depends on the proximity of the two MPP voltages.

The previous considerations are true when, as it often happens, both the characteristics don't have inflection points. Let's suppose that the MPPT circuits, while trying to maximize the power, have brought the system to the condition of figure 4, where the two duty-cycles are equal to d_{max}. Given the value of the apparent load resistance R_L, the duty-cycle must be the same for the two generators, since P_1B can't move to the right (towards a lower d_{PV}) because it's already $d_{WT}=d_{max}$ and BP_1' can't move to the left, and viceversa, without reducing V_{bus} and, consequently, $P_L=\frac{V_{bus}^2}{R_L}$. Therefore the MPPT logic can only decide to change the value of R_L, so that point P is moved above the hyperbole (blue dashed) related to the corresponding value of power (P_L). However this is hardly possible.

Decreasing R_L, with constant voltage V_{bus}, a higher current is needed, i.e. the segment P_1P_1' should move to the left, but doing so it will not respect the condition on the duty-cycle; therefore V_{bus} should decrease and the two operating points would move farther from both the MPPs.

On the contrary, increasing R_L the auxiliary curve should be considered (blue solid), which can be obtained from the hyperbole P_L by right shifting it by a quantity which equals the segment AB, and by moving down the latter curve by subtracting from it the corresponding ordinate of the WT characteristic. This curve represents the locus of the currents requested to the PV generator to maintain the same power P_L when the DC-link voltage varies. To achieve a higher power at least a portion of the PV characteristic around the MPP should be above the new curve.

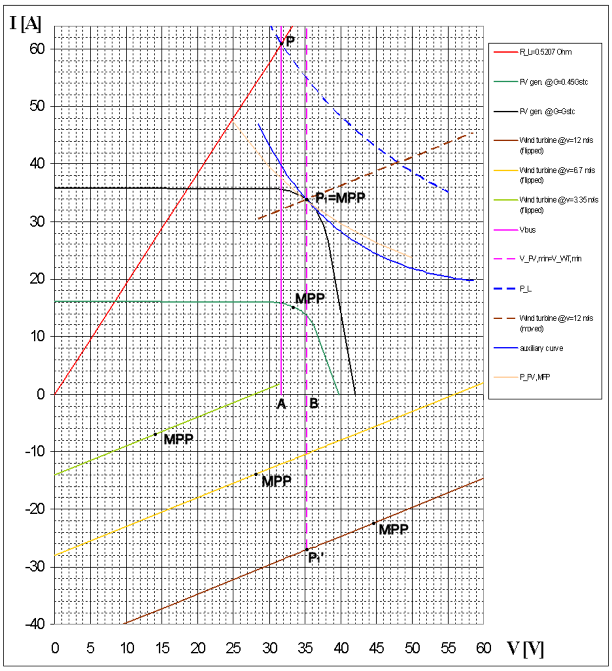

Fig. 4. Graphical construction for a PV-wind HRES with constant DC-link voltage with $d_{PV}=d_{WT}=d_{max}$

This condition implies the availability of operating points with lower current and higher power and V_{bus}. The portion of the new curve which corresponds to operating points with a higher power is dramatically small (figure 5) and it reduces as the internal resistance of the wind generator decreases. By performing a simulation for the considered system, the distance between the true MPP (figure 6) and the supposed MPP is insignificant (+0.05% on the power).

Therefore, as to the optimisation of the grid-connected operation, the previous considerations are proved; furthermore it is possible to say again that the maximum $V_{WT,MPP}$ must be lower than the maximum $V_{PV,MPP}$, otherwise the operating point will never be close to the first MPP voltage.

Further considerations can be made. Shmilovitz showed that, among the various algorithms aimed at finding the MPP, the maximization of the output parameters [8] (e.g. V_{bus}) can be used, but the limits of the voltage increase were not discussed, nor it was the operation with two generators.

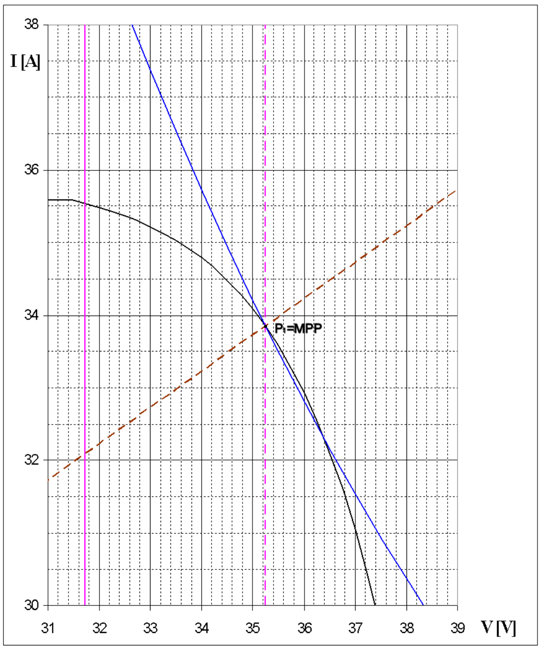

Fig. 5. A zoom around point P_1 in figure 4 (supposed MPP)

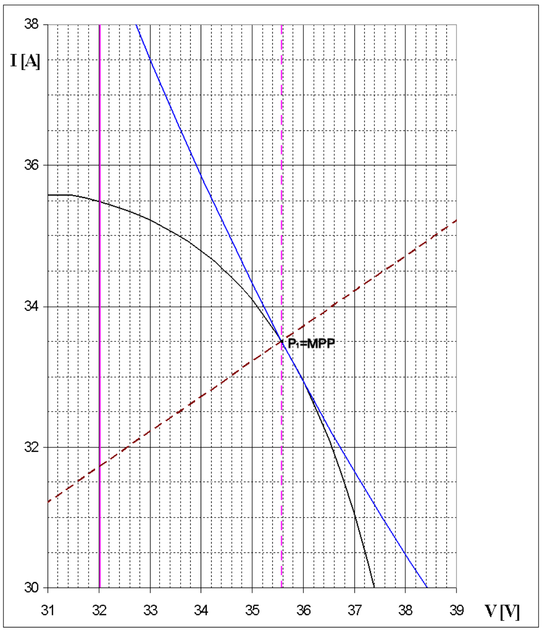

Fig. 6. A zoom around point P_1 in figure 4 for a different value of R_L (true MPP)

In the present work, besides confirming the relationship between the voltage on the DC-link and the deliverable power, it has been proved that the first physical quantity, in the hybrid grid-connected operation, always settles on a value which is in the range defined by $d_{max}\cdot V_{PV,MPP}$ and $d_{max}\cdot V_{WT,MPP}$, included the lower and upper bound; in the hybrid stand-alone operation, instead, the quantity $V'_{bus}=\min\{d_{max}\cdot V_{MPP\_non\_linear\_generator};\ E_{storage};\ V_{load,max}\}$ represents the maximum voltage which can be obtained by varying the load resistance R_L.

Moreover, the maximum value of the deliverable power will be equal to $d_{max}\cdot P_{MPP}$ for a non hybrid RES, while for a HRES it will be a quantity which is less or equal to $d_{max}\cdot(P_{PV\_MPP}+P_{WT,MPP})$ and that will depend on the difference of the MPP voltages of the two generators.

Therefore it is worth noting that a possibility exists to unify both the circuital topology, and the software and hardware (included the sensors: a single voltage sensor on V_{bus} will suffice) involved in the control of the PWM converters. In both cases the goal will consist on increasing the voltage V_{bus} as much as possible, yet respecting the previous limits:

- *in the stand-alone operation the duty-cycle should be modified in order to impose the set-point voltage V'_{bus};*
- *in the grid-connected operation the apparent load resistance R_L should be varied in order to maximize the voltage V_{bus}, keeping at the same time the duty-cycles constant and equal to the maximum value d_{max}.*

3. System design

The previous considerations entail a matching between the prevalent generator, the storage system, the chosen DC-link voltage and the limit to the load voltage. Therefore, a new configuration in terms of circuit topology and control technique is proposed.

The chosen topology is the VSI multistring inverter with a low voltage DC-link and a line frequency transformer, coupled with a DC/DC buck converter for each generator and a bidirectional buck/boost converter for the storage device (figure 7). The latter converter allows to step-up the battery voltage during the discharge on the DC-link and to step it down during the charge operation. This solution reflects the topology of stand-alone systems, in which the DC-link must operate at a voltage level which has to be compatible with the storage device; this operation mode can be therefore optimised, since the voltage on the DC-link can be regulated to be close to the MPP of the prevalent (non linear) generator.

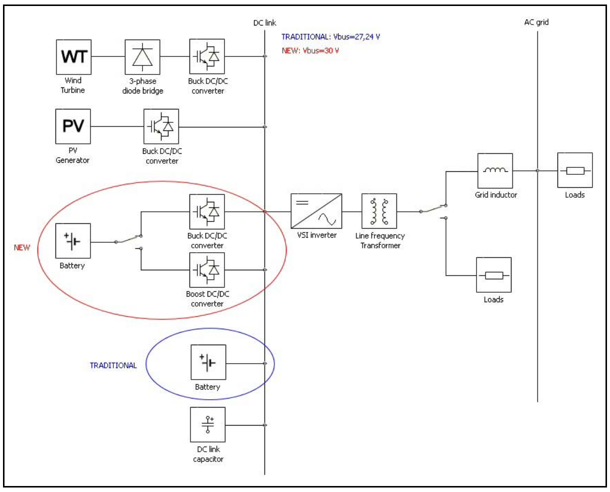

Fig. 7. Traditional and new circuit topologies

On the contrary, the grid-connected operation, cannot be further optimised. However, by varying the control of the converters, this topology allows the operation in grid-connected mode without circuital modification, with a relevant advantage in safety, size reduction and cost due to the low operating voltage of the capacitors.

All the converters are controlled by PID regulators designed with traditional methods [9] aimed to get suitable steady state error, bandwidth and stability margins. In the stand-alone operation, the control logic of the buck converters connected to the generators and to the battery tries to maintain the DC link voltage constant and equal to the highest possible value, respecting the previously discussed limits. The boost converter, on the contrary, will impose the optimal voltage for the battery charging.

Differently, in the grid-connected operation, the control of the converters must implement a MPPT algorithm and must vary the apparent resistance to maximize the power produced and injected into the grid. As stated before, instead of using expensive current sensors or computing the power by multiplying voltage and current, V_{bus} can be maximized, provided that the duty-cycles are kept constant and equal to d_{max}.

4. Simulation

The proposed solution has been verified, both in stand-alone and grid-connected operation, by simulating the system with Simulink and PLECS® in several scenarios which use real data coming from an existing 2.2 kW_p PV-Wind-battery system [10], set-up at D.R.E.AM., which has been properly modelled in form of a block diagram (figures 8 and 9). Being very small quantities, the losses have been neglected.

On the basis of a one-year campaign of environmental data monitoring, nine scenarios have been identified by intersecting three values of solar radiation (100, 450 and 1000 W/m^2) with three values of wind speed (3.35, 6.7 and 12 m/s).

Nine series of tests have been performed in order to evaluate the performance of the system as the load and the operating conditions vary. In the first series of tests the design of the different DC/DC converters has been validated successfully.

In the second and third series, the non hybrid PV system has been simulated, respectively for both the traditional and new configurations. Summarizing tables

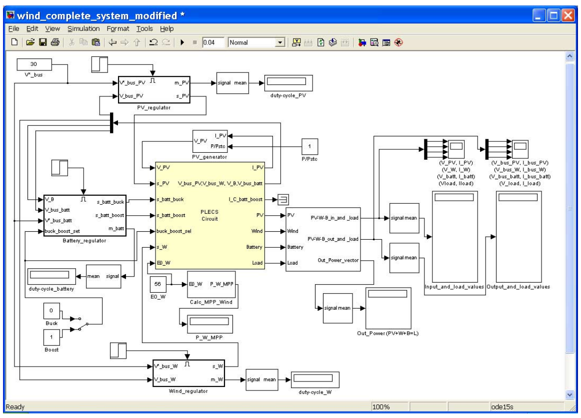

Fig. 8. The Simulink model of the system in the new configuration

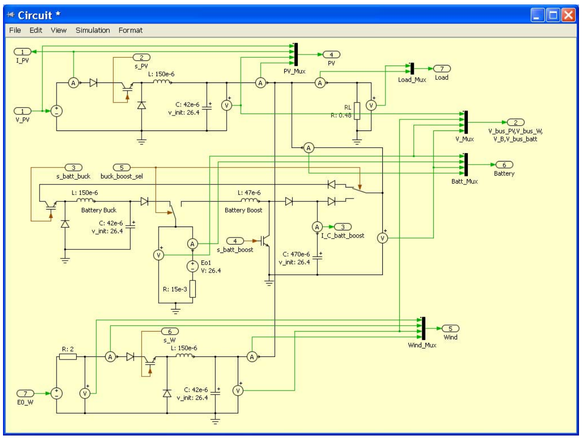

Fig. 9. The PLECS electrical scheme of the system in the new configuration

have been filled with the values of several quantities: voltages, currents, duty-cycles, powers, increments in power, etc. The simulations show the validity of the new configuration, since the power produced is always higher than the value related to the traditional configuration (figure 10). The threshold to switch from buck to boost mode has also been defined: it has been obtained by sensing the reduction of the current from/to the battery with an hysteresis comparator. In addition it has been noticed that the results can be scaled proportionally for values of the solar radiation lower that the standard value G_{stc}.

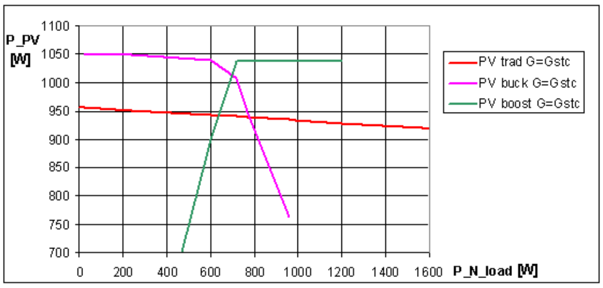

Fig. 10. Power produced by the PV generator vs. load power, for $G=G_{stc}$

Similar tests have been performed in the 4^{th} and 5^{th} series, which are related to system supplied by the WT alone. However, an increase in the production is attained only for high wind speed, as expected; furthermore the results cannot be scaled proportionally for different operating conditions. However, it is possible to implement a fallback mode, to operate the system in the traditional way when the new strategy is not convenient.

Series number 6 deals with the hybrid system in the traditional configuration, while series 7 and 8 are related to the new hybrid configuration, respectively for the buck and boost operation of the DC/DC converter which connects the battery to the DC-link. The simulations have been performed in the nine scenarios and they show that, in the new configuration, the production increment due to the presence of the PV generator compensates almost completely the decrement exhibited by the wind turbine alone.

Moreover, as previously said, the power produced by each generator is lower than the theoretical MPP value, but in the new configuration higher values are experienced compared to the traditional operation.

Finally, the 9th series is related to the evaluation of the annual energy produced by the hybrid system in the three most probable scenarios according to the results of the monitoring campaign, i.e. those related to corresponding levels of solar radiation and wind speed (max-max, med-med, min-min). As to the grid-connected operation, even if no models were available for the simulation of MPPT circuits, it has been possible to perform the simulation by means of a preliminar identification of the maximum power condition, carried out with the graphical analysis.

5. Analysis of the results

The results of the simulations related to the hybrid configuration have been analysed and they confirm that in the stand-alone operation a significant increase in the power supplied can be achieved in 7 of the 9 scenarios, up to 13.73% according to the operating conditions of the generators and to the load power level, starting from a small fraction of the nominal power of the system. This also implies a higher continuity of the energy supplied to the load.

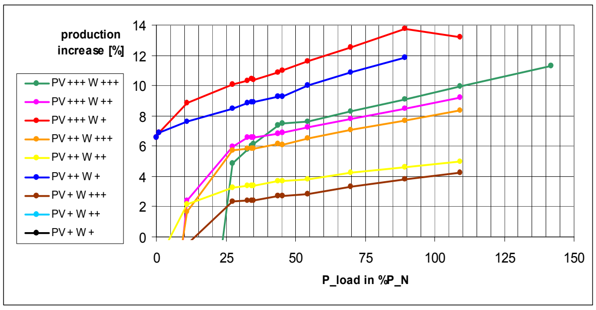

Fig. 11. Production increase vs. load power level in several operating conditions for solar radiance and wind speed: +++=maximum, ++=average, +=minimum

Furthermore, it is possible to implement a fallback mode, to operate the system in the traditional way when the new strategy is not convenient; thus a 0% increase in the production (instead of a negative one) can be obtained, as it is shown in the last two curves (light blue and black) of figure 11.

The two parts of each curve (related to buck and boost mode) can be easily interpolated with Excel, with a confidence parameter R^2 which is very close to the unity. An investigation about this behaviour could allow to model the system conveniently.

As for the produced annual energy, the analysis shows an increase between 4% and 5.5% for two typical load resistance values in the stand-alone configuration, corresponding to half the nominal load and to a 14% overload. It shows also a non perfect fit with the typical data given by the manufacturers for the grid-connected operation. The simulation showed a production of 3492 kWh (1656.5 kWh from WT; 1835.5 kWh from PV), corresponding to the needs of an average family made up of four persons; the values advertised by the manufacturers are 1080 kWh from WT, 2160 kWh from PV for a total of 3240 kWh.

In order to carry out the experimental verification of the circuital topology and of the control technique, a test bench is going to be built and installed at the mobile house.

6. Conclusions

The use of a buck/boost converter to interface the storage device to the DC link allows a significant increase in the power supplied by the renewable sources, thus maximizing the operating efficiency. The annual energy produced by the whole system is increased too. Finally, a non perfect matching with the rated data given by the manufacturers has been noticed.

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