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Influence of Power Converter Losses Evaluation in the Sizing of a Hybrid Renewable Energy System

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Abstract— An improvement to the precision of losses calculation in static converters used in a hybrid renewable energy system (HRES) is presented in this article. The objective is to be able to evaluate energy losses in the system during the unit sizing process. The models developed in this paper consider the conduction and switching losses to take into account the variation of the converters efficiency together with the load variations. The proposed approach for the energy losses calculation is tested with an already sized HRES. The methodology is compared on an hour-by-hour basis with a constant efficiency rate approach using a specially developed simulation program. The importance of the correct energy losses evaluation is demonstrated.

Index Terms—power conversion losses, power generation, solar energy, wind energy

I. NOMENCLATURE

r_D	Diode internal forward resistance (Ω)
V_D	Diode forward voltage threshold (V)
I_D	Diode average current (A)
$i_{D,RMS}$	Diode effective current (A)
p_D	Diode conduction losses (W)
r_T	Transistor internal forward resistance (Ω)
V_T	Transistor forward voltage threshold (V)
I_T	Transistor average current (A)
$i_{T,RMS}$	Transistor effective current (A)
p_T	Transistor conduction losses (W)
p_R	Rectifier conduction losses (W)
D	DC/DC converter duty cycle (-)
t_{on}	DC/DC converter transistor on-state time (s)
t_{off}	DC/DC converter transistor off-state time (s)
I_L	DC/DC converter average current (A)
$i_{L,RMS}$	DC/DC converter effective current (A)
$p_{dc/dc}$	DC/DC converter conduction losses (W)
I_m	Converter steady-state maximal current (A)
M	Inverter modulation index (-)
φ	Inverter load angle (rad)
$p_{dc/ac}$	Inverter conduction losses (W)
I_N	Converter nominal current (A)
t_{rN}	Switch turn-on time at nominal conditions (s)
t_{fN}	Switch turn-off time at nominal conditions (s)
t_{rrN}	Nominal reverse recovery time (s)
Q_{rrN}	Nominal reverse recovery charge (C)
f_s	Converter switching frequency (Hz)

$p_{c, on}$	Turn-on switching losses (W)
$p_{c, off}$	Turn-off switching losses (W)
p_{rr}	Recombination losses (W)

II. INTRODUCTION

A Hybrid Renewable Energy Systems (HRES) is a power generation system composed of two or more energy sources where at least one of them is of renewable origin. Applications in this type of system include water pumping through DC motors operating centrifugal pumps, vaccine storage, rural electrification in developing countries, etc; particularly in isolated places where to dispose energy from the grid is expensive or even impossible [1]-[2].

To motivate the use of HRES, an appropriate assessment for unit sizing a renewable energy system must be made in order to reduce the overall cost of the energy produced while achieving acceptable reliability conditions. In general, energy losses of the wind turbine (WT), diesel generator (DG) and photovoltaic (PV) panels are estimated with some level of accuracy in order to calculate the total amount of energy supplied by each source. The energy losses of the power converters become an important issue in unit sizing of renewable energy systems because of its influence on the total energy delivered to the load. For many years, authors have treated the problem of the energy losses estimation in power converters [3], [4], [5] in a wide scope of applications but not specifically in the renewable energy systems area. Previously, some efforts have been made in order to take into account the energy losses in power converters within a unit sizing procedure. In [6] and [7], an iterative approach inside the unit sizing procedure is proposed using constant efficiency rates.

In this article, a new approach to estimate the energy losses in the power electronics converters is proposed. The equations are developed considering the special characteristics of a small hybrid renewable energy systems and its operation. A DG, WT, PV solar modules, and a battery bank compose the hybrid system. The unit sizing procedure takes into account the economical aspects of each generating unit and stochastic nature of renewable energy sources. The energy losses estimation is included within the unit sizing procedure. The results are compared with a constant efficiency approach.

This paper begins with the description of the proposed models. The next section describes the models developed to estimate the conduction losses in the rectifier and the switching and conduction losses in the inverter and the PV's maximum power point tracker (MPPT). In the fourth section, the simulation results are shown in order to display the application of the proposed models. Finally, some conclusions and perspectives of this work are exposed.

III. PROPOSED METHOD

A. System description

The system under study contains a three-phase DG connected through a rectifier to the DC bus, a WT also connected to the DC bus through a diode bridge, PV solar panels with a Maximum Power Point Tracker (MPPT), a battery bank for energy storage and back-up, and one inverter to transfer the required power to the load. The system is shown in Fig. 1.

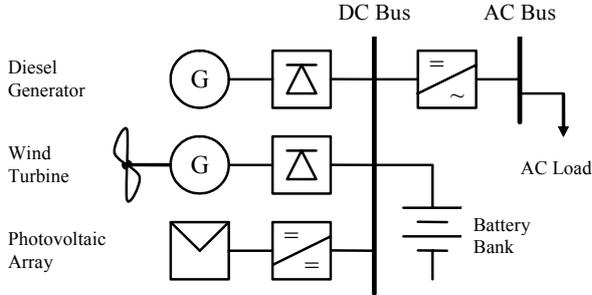


Fig. 1. Hybrid renewable energy system composed of wind and photovoltaic power sources, a diesel generation unit, a battery bank and one inverter.

There are two power transformers in the system. One is a three-phase step-down transformer that connects the DG to the rectifier and the other is a single-phase step-up transformer that connects the inverter output to the system electric load. In this study, as transformers are operating at low-voltage and low-frequency, iron losses are neglected. Therefore, since only the copper losses are taken in account, the transformers are modeled as simple equivalent series impedances.

The load has a nominal voltage of 220V/50 Hz as well as the DG (phase-to-neutral voltage). Power MOSFETs are used as switches in the controlled power electronics converters. The switching frequency of the PWM converters is chosen at 20 kHz, for audible noise cancellation, at low EMI and low switching losses. For security reasons, the DC bus voltage is 48 Volts. To avoid annoying effects on the system load, a passive harmonic filter is connected at the inverter output. This filter is considered to be ideal, so it is free of energy losses.

B. Unit Sizing Procedure

The procedure to make an economic choice of the size of each generating unit is based on the minimization of

the life cycle cost that implies an economic analysis over the lifetime of the project. A supplementary procedure for sizing the storage battery and the DG is used.

In order to evaluate the quality of the design, a simulation program was specially developed. To calculate the hourly energy flow, the mathematical models for the WT and the PV solar panels are used. Wind speed and solar irradiance data are needed to calculate the total energy produced by the wind turbine and the solar module. Their Probability Distribution Function (PDF) characterizes the behavior of these variables.

One important step in the unit sizing procedure is the energy non supplied (ENS) calculation. In this step, the right estimation of the energy losses in the system is a key point. Detailed information about the unit sizing procedure can be found in [7].

C. Energy Losses Calculation

The analysis is made taking into account the wave forms of voltages and currents in the system.

The proposed HRES AC/DC converters connected between the DC bus and the wind turbine and the diesel generator are simple three-phase diode bridges, thus only conduction losses are considered. The DC/DC converter connected between the solar panels and the DC bus, and the inverter connected between the DC and the AC buses are switch-mode operated converters. In this case, the switching frequency is much higher than the system's frequency. Therefore, switching losses are not negligible and must be calculated.

D. Diode Conduction Losses

The diode's model used to evaluate on-state losses in power electronic converters is shown in Fig. 2, where r_D is the ON-state diode resistance and V_D is the threshold forward voltage necessary to put the diode in conduction state. These parameters are characteristics of the diode.

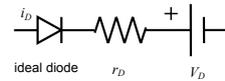


Fig. 2. Diode model for ON state losses calculation

Conduction losses in each diode can be calculated as follows, where I_D is the average diode current and $i_{D\text{ RMS}}$ is the effective diode current.

$$P_{diode} = V_D \cdot I_D + r_D \cdot i_{D\text{ RMS}}^2 \quad (1)$$

E. Power transistors Conduction Losses

Gate-controlled switching semiconductors are used to modulate the static power converters of the proposed hybrid system. The switch-mode converters are the PV array maximum power point tracker (MPPT), implemented with a DC/DC converter, and the inverter that feeds the hybrid system ac load.

A simple general model for transistor on-state is used to evaluate conduction losses. It is analog to the previous

diode model, but changing the ideal diode for an ideal unidirectional switch. This model can be applied to both IGBT and MOSFET power transistors, where V_{ON} is set to 0 when using a MOSFET. Thus, on-state transistor losses in both switching power converters of the HRES can be calculated by (2).

$$p_T = V_{ON} \cdot I_T + r_{ON} \cdot i_{T,RMS}^2 \quad (2)$$

F. Diode Bridge Rectifier Conduction Losses

The diode bridge generates distorted line currents and/or voltages depending on the load and/or source characteristics. For a strong power source, like a large utility grid, with a high inductive DC load, the output current is nearly constant and line currents have a six-pulse shape [8]. But in the case under study, the DC bus has a battery bank that behaves like a constant DC voltage source, thus like a high capacitive load. Fig. 3 shows the electrical scheme from the generator to the DC bus. Moreover, the source is a small diesel or wind generator that usually has high inductive windings. Therefore, supposing the generator voltage and inductances sufficiently important, the source currents are nearly sinusoidal. The line voltage has the 6 pulses shape, with a maximal value given by the battery bank voltage.

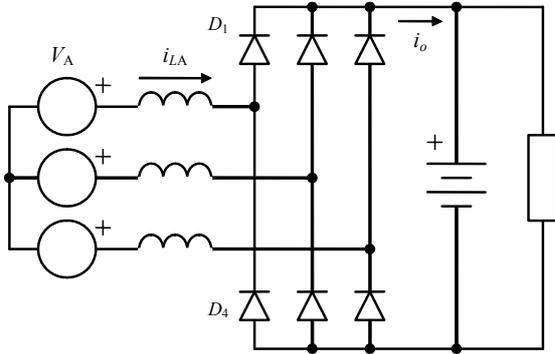


Fig. 3. Three-phase bridge diode rectifier with a high inductive electrical power source and a high capacitive DC load

These sinusoidal currents flow through the diodes. To evaluate conduction losses with (1), it is necessary to calculate the average and effective values of the diode currents. These values can be expressed in terms of the input line current i_L (3), or in terms of the DC output current I_o (4). These expressions are valid for continuous mode of conduction; *i.e.*, the current in one diode extinguishes only because other diode begins its conduction cycle and the output current value is always higher than zero. This is very probable due to inductive behavior of the source. Fig. 4 shows the rectifier AC input currents in one phase (composed of diode currents i_{D1} and i_{D4}) and the output current i_o .

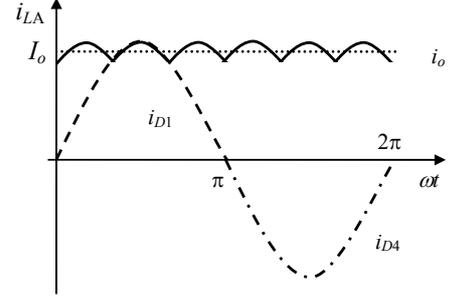


Fig. 4. Diode bridge current waveforms; input line current i_{LA} composed by i_{D1} and i_{D4} currents and output current i_o

$$I_D = \frac{\sqrt{2}}{\pi} i_L = \frac{1}{3} I_o \quad (3)$$

$$i_{D,RMS} = \frac{\sqrt{2}}{2} i_L = \frac{\pi}{6} I_o \quad (4)$$

Since every diode has similar characteristics and the normal operation of the rectifier implies equal but 120 degrees out-of-phase currents in all components, conduction losses can be expressed as follows (5), (6).

$$p_R(i_L) = 6 \cdot p_{diode} = \frac{6\sqrt{2}}{\pi} \cdot V_D \cdot i_L + 3\sqrt{2} \cdot r_D \cdot i_L^2 \quad (5)$$

$$p_R(I_o) = 6 \cdot p_{diode} = 2 \cdot V_D \cdot I_o + \frac{\pi^2}{6} \cdot r_D \cdot I_o^2 \quad (6)$$

G. DC/DC Converter Conduction Losses

The following conduction losses analysis is made for a one single-stage DC/DC power converter; *i.e.*, only one transistor-diode pair is used for the DC/DC conversion. Continuous current mode is assumed in the converter operation; *i.e.*, the main current flows without extinguishing through the power semiconductors for each conduction state. The transistor conducts the converter current during "ON" state (t_{on}) and the diode the converter current in the "OFF" state (t_{off}). D is the transistor duty cycle [8]. In Fig. 5, the transistor, the diode and the inductor current shapes for two switching cycles are shown. From this figure, equations for the average and effective currents of the transistor and the diode (8) and (9) are obtained. I_T , I_D , and I_L are respectively the transistor, diode and inductance average currents and $i_{T,RMS}$, $i_{D,RMS}$ and $i_{L,RMS}$ are the transistor, diode and inductance effective currents.

$$D = \frac{t_{on}}{T} \quad T = t_{on} + t_{off} \quad (7)$$

$$I_T = D \cdot I_L \quad i_{T,RMS} = \sqrt{D} \cdot i_{L,RMS} \quad (8)$$

$$I_D = (1 - D) \cdot I_L \quad i_{D,RMS} = \sqrt{1 - D} \cdot i_{L,RMS} \quad (9)$$

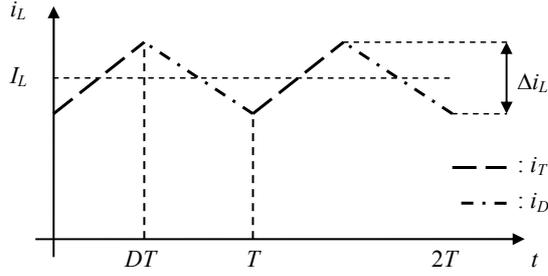


Fig. 5. Steady state inductor current waveform i_L composed by transistor and diode currents (i_T, i_D) for two cycles of a one single step DC/DC converter

Conduction losses in basic switching converters occur in both state conditions; during ON-state, the power transistor wastes some energy and during OFF-state, the freewheeling diode generates the power dissipation. Replacing correspondently (8) and (9) in conduction losses equations (1) and (6), (10) and (11) are obtained. By adding these last equations, conduction losses in the basic DC/DC converter can be calculated with (12).

$$p_T = D \cdot (V_{T,ON} \cdot I_L + r_{ON} \cdot i_{L,RMS}^2) \quad (10)$$

$$p_D = (1-D) \cdot (V_{D,ON} \cdot I_L + r_D \cdot i_{L,RMS}^2) \quad (11)$$

$$p_{dc/dc} = (D \cdot V_{T,ON} + (1-D) \cdot V_{D,ON}) \cdot I_L + (D \cdot r_{T,ON} + (1-D) \cdot r_D) \cdot i_{L,RMS}^2 \quad (12)$$

The static converter's DC current i_L and effective current $i_{L,RMS}$ are not equal because there is an alternative triangular shape component $i_{L,AC}$ of the inductor current created by transistor to diode current switching, charging and discharging the inductor alternatively (Fig. 5). This AC component is proportional to current ripple Δi_L and it is dependent of the converter switching frequency f_s and the inductance value L , among others converter parameters.

The DC/DC converter design for continuous conduction mode generally limits Δi_L to a specific percentage of the DC current (between 5 or 10 percent of inductor current). The worst case happens when converter operation is in the border of discontinuous mode; *i.e.*, the main current extinguishes at the end of the switching period in steady state. This is a 200% of ripple in converter current, an unusual high value for continuous mode design considerations. Anyway, even if this happens, the effective current $i_{L,RMS}$ is only 15,5% higher than average current I_L . Therefore, supposing this worst case, (12) can be expressed as (13).

$$p_{dc/dc} = (D \cdot V_{T,ON} + (1-D) \cdot V_{D,ON}) \cdot I_L + \frac{4}{3} (D \cdot r_{T,ON} + (1-D) \cdot r_D) \cdot I_L \quad (13)$$

H. Inverter Conduction Losses

The hybrid system in study is designed to supply energy to a small single-phase isolated load, so a simple H-Bridge inverter is proposed to deliver regulated AC

voltage from the DC bus (Fig. 6). To simplify the design and to minimize the size of the output filter that connects the inverter and the load, pulse-width-modulation (PWM) control is used. Thus, losses are produced by conduction and switching in the semiconductors. So, as in the DC/DC converter, these two kinds of energy losses must be calculated.

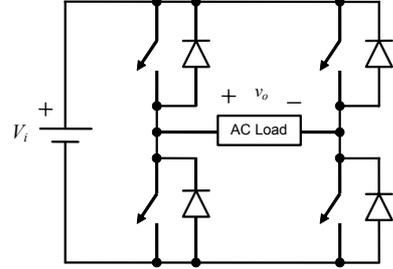


Fig. 6. HRES inverter power circuit

The analytical method proposed in [4] is used to evaluate the PWM inverter conduction losses. With (14) and (15) conduction losses for one transistor-diode pair are calculated. These are expressed in terms of semiconductor characteristics (r_D, V_D, r_T, V_T) and converter variables like maximal current I_m , modulation index M and load angle φ . For the H-structure DC/AC converter (16) calculates total conduction losses.

$$p_T = \frac{V_T I_m}{2\pi} \left(1 + \frac{\pi}{4} M \cos \varphi \right) + \frac{r_T I_m^2}{2\pi} \left(\frac{\pi}{4} + \frac{2M}{3} \cos \varphi \right) \quad (14)$$

$$p_D = \frac{V_D I_m}{2\pi} \left(1 - \frac{\pi}{4} M \cos \varphi \right) + \frac{r_D I_m^2}{2\pi} \left(\frac{\pi}{4} - \frac{2M}{3} \cos \varphi \right) \quad (15)$$

$$p_{dc/ac} = 4(p_T + p_D) \quad (16)$$

I. Switching Losses

Many distinct variables influence this kind of losses in static converters: temperature, current, semiconductor material, etc. In the study of a system composed of at least one PWM controlled converter, switching losses can not be neglected when the system losses are calculated.

The analytic approach to calculate losses during commutation proposed in [5] is used in this article. This model considers the most important components of these losses for evaluation: turn-on losses $P_{c,on}$, turn-off losses $P_{c,off}$, and recombination losses P_{rr} . To make this calculation, it is necessary to know the maximal blockage voltage V_m , maximal and nominal currents I_m and I_N , the converter switching frequency f_s and the raise and fall times at nominal conditions t_{rN} and t_{fN} . To estimate recombination losses it is also necessary to know the nominal recombination time t_{rrN} and charge Q_{rrN} . The hybrid system PWM converters switching losses are evaluated using (17) - (19).

$$p_{c,on} = \frac{1}{8} V_m \frac{I_m^2}{I_N} t_{rN} f_s \quad (17)$$

$$p_{c,off} = V_m I_m t_{fN} f_s \left(\frac{1}{3\pi} + \frac{1}{24} \frac{I_m}{I_N} \right) \quad (18)$$

$$p_{rr} = V_m f_s \left[\left(\frac{0.8}{\pi} + 0.05 \frac{I_m}{I_N} \right) \cdot I_m t_{rrN} + \left(0.28 + \frac{0.38}{\pi} \frac{I_m}{I_N} + 0.015 \left(\frac{I_m}{I_N} \right)^2 \right) \cdot Q_{rrN} \right] \quad (19)$$

IV. RESULTS

The proposed approach for the energy losses calculation is tested with an already sized HRES. The methodology is compared on an hour-by-hour basis with a constant efficiency rate approach using a specially developed simulation program.

The daily average solar radiation on a horizontal surface in the selected place is 4.61 kWh/m² and the average wind speed is 6.1 m/s. The hourly load profile for one day is shown in Fig. 7.

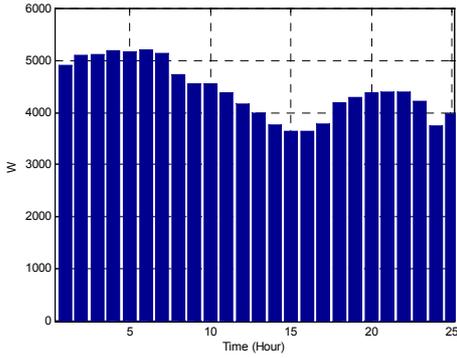


Fig. 7. Hourly load profile for one typical day.

The energy production of the HRES for the constant efficiency rate and for the proposed variable efficiency rate approaches are shown in Figures 8 and 9 respectively. Each power source generation is plotted for each hour of the day, for a typical day. The state of charge of the battery bank is also shown, as well as the load profile and the energy balance. From the latter the ENS value is obtained by integration of the negative values.

In the constant efficiency rate approach, the efficiency of all power converters is set at 90%. The system is first simulated using this constant efficiency rate approach. The energy supplied by each generating unit and the energy demanded by the load are shown in Fig. 8. The diary total lack of energy is 13.8 kWh.

The system is then simulated using the proposed losses calculation approach for calculating energy losses in the HRES. Fig. 9 shows the energy supplied by each generating unit and the energy demanded by the load. The lower efficiency rates calculated using the proposed methodology give as result a diary total lack of energy

equal to 34,5 kWh. In this case, the calculated energy non supplied to the load (ENS) is about 40% higher when used the proposed method.

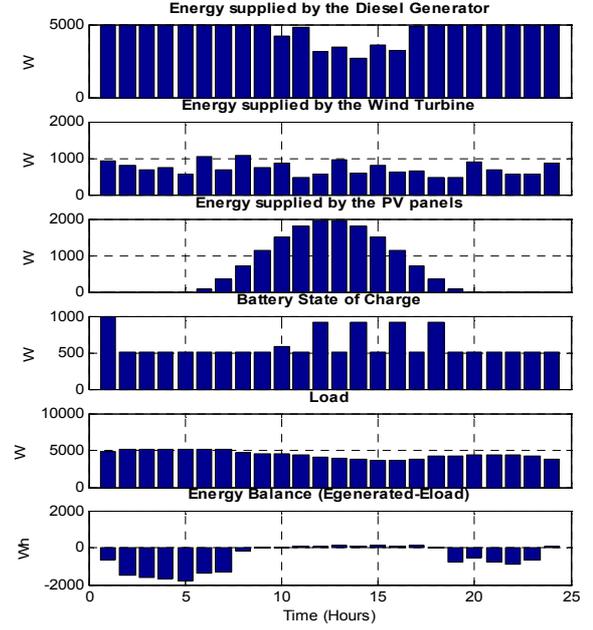


Fig. 8. HRES energy production for 24 hours of a typical day at constant efficiency rates. Different power sources generation, the battery state of charge, load profile and energy balance.

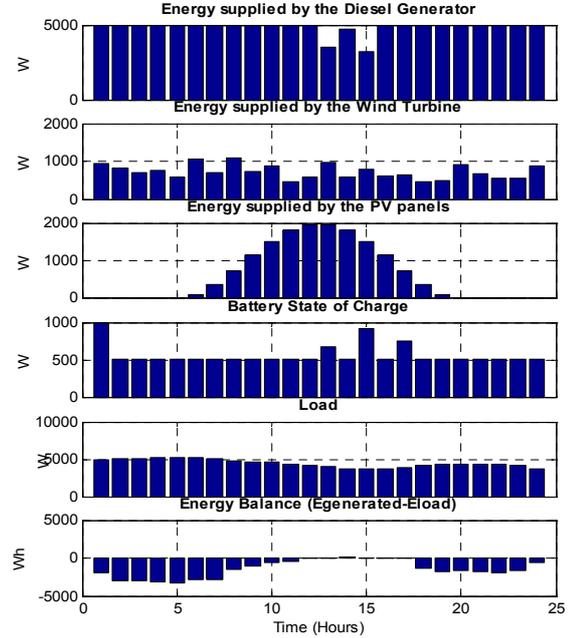


Fig. 9. HRES energy production for 24 hours of a typical day at variable efficiency rates (proposed evaluation). Different power sources generation, the battery state of charge, load profile and energy balance.

This large difference in ENS estimation is explained by an overall efficiency lower than the 90% supposed in the constant efficiency method; this way, the total energy delivered by the HRES is lower than expected and,

therefore, the lack of energy is higher. The more accurate evaluation of losses done by the proposed method includes operating points other than nominal, where efficiency is lower most of the time. It includes also most of losses in all power converters (transformers and electronic devices); thus, a higher ENS calculation was expected and finally obtained.

From the analysis of the results it can be seen that the energy losses calculation have a significant effect over the calculation of the long-term system performance. The right estimation of parameters such as the energy non supplied to the load is important when unit sizing a renewable energy system and are strongly influenced by the total energy losses.

V. CONCLUSION

In the analysis of renewable energy systems, the constant efficiency approach is generally used when analyzing the long-term system's behavior. This is especially important when more precise losses estimation is needed in order to calculate the available energy that can be delivered to the load. In this article, a novel approach for the energy losses calculation in a HRES is proposed.

The proposed method allows taking into account variable energy losses during the system operation. Models for the conduction and switching energy losses are used and adapted to the special characteristic of each power electronic converter in the system. Assumptions on the system operation are made in order to obtain analytical expressions for the power converter energy losses. The proposed method is then compared with the constant efficiency rate approach. It can be noticed that using the constant efficiency approach one could underestimate the total energy losses in the system.

Related to the energy losses calculation, only one possible system topology is analyzed in this article. The work can be continued including new topologies and new equipments. Also, the DC bus voltage can be elevated in order to reduce the value of the current and so the total energy losses.

APPENDIX

The principal parameters of the system are summarized in the following table:

TABLE I
SUMMARY OF THE HRES PARAMETERS

Diesel Generator	
Rated voltage	220 V
Rated power	5000 W
Rectifier Diodes	
Rated voltage	800 V
Rated current	10 A
Conduction voltage	1.1 V
Conduction resistance	20 mΩ
MOSFET	
Rated voltage	150 V

Average current	60 A
Conduction voltage	0 V
Conduction resistance	0.04 Ω
t_{FN}, t_{FN}	40 ns, 40 ns
t_{FN}, Q_{FN}	150 ns, 2.0 μC
Fast recovery diodes	
Rated voltage	200 V
Average current	20 A
Conduction voltage	1.3 V
Conduction resistance	12.5 mΩ
Transformers	
Three-phase step-down	
Rated power	6000 W
Equivalent resistance	0.05 Ω
Single-phase step-up	
Rated power	5000 W
Equivalent resistance	0.15 Ω
Wind turbine	
Rated wind speed	14 m/s
Rotor diameter	3.7 m
Rated power	3.0 kW
Rotor speed	150/900 rpm
Solar Panels (18 180W-panels)	
Peak power	3 kW
Rated voltage	36 V
Rated current	5 A

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