Modeling and the Impact on Power Quality of Hybrid Solar – Wind Power Plants

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Abstract — **Many renewable energy sources are not able to provide the demanded electrical energy during the day. This problem is getting more important with the increase of power plants which are based on renewable energy. The proposed method for overcoming the aforementioned problem is the building of hybrid power plants with two or three different energy sources. The most common hybrid power plants are solar–wind power plants, who produce electricity by using the complementary characteristics of solar irradiation and wind speed. The hybrid solar–wind power plants contain a lot of power electronic devices that affect the power quality disturbances. Therefore, an analysis of the dynamic of such power plants is necessary. First part of this paper presents the modeling of hybrid solar–wind power plants. The second part analyzes the impact on power quality of hybrid solar–wind power plant during its daily working cycle.**

Keywords—hybrid; solar; wind; power quality; modeling.

I. INTRODUCTION

Many changes in law regulations in the field of electrical energy, the requirements for the sustainability of national energy systems together with the environmental requirements favored the occurrence of distributed generation of electrical energy and new ways of using primary energy resources. Distributed electrical sources supply local consumption areas and in that way, they lower the energy losses and fix the line voltage drops. The primary energy sources for distributed generators mainly have renewable nature, and for that reason distributed generation is an ecological clean solution and that is its biggest advantage. [1]

The critical disadvantage of distributed generation which is based on renewable energy resources is the inability of sustainable energy production during a long period of time. Therefore, it is not possible to rely on this type of energy production. This disadvantage leads to the fact that renewable energy sources can't yet be used as base units for energy production in power systems and that role is still given to fossil fuel and nuclear power plants. But, that changes when it comes to the combination of two or more renewable energy sources which can lead to sustainable renewable energy based system for energy production. Hybrid power plants overcome the inability of sustainable energy production during a long period of time. The two most popular renewable energy sources, wind power plants and photovoltaic power plants are a great potential for hybrid power plants. Wind power plants and photovoltaic power plants are based on primary energy sources which have a cyclic change during a period of time. That can be seen from the daily change of solar irradiation and wind speed. However, solar irradiation and wind speed have a mutual complementary characteristic. The mutual complementary characteristic of these two energy sources can be seen on daily and on annual bias.

Table 1. shows the monthly value of wind speed and solar irradiation for the same analyzed area. [2].

TABLE I. THE RESOURCES OF WIND AND SOLAR ENERGY AS A PERCENTAGE OF THEIR ANNUAL MAXIMUM

Month	***Wind speed***	***Solar irradiation***
January	100 %	29 %
February	79 %	36 %
March	60 %	62 %
April	41 %	71 %
May	19 %	77 %
June	9 %	100 %
July	0 %	89 %
August	20 %	80 %
September	40 %	78 %
October	58 %	68 %
November	80 %	41 %
December	100 %	32 %

This technology is still under development and therefore it is necessary to carefully analyze the possibility of modeling of hybrid solar–wind power plants in some area. In future, hybrid solar–wind power plants could take the base energy production role from fossil fuel and nuclear power plants. Thus, the negative characteristic of wind power plants and photovoltaic power plants in aspect of power quality can be a really hard meeting criteria for hybrid solar–wind power plants. These two power plants, even when installed independently, have big influence on power quality, and so their combination with all the dynamics and the interference in work needs to be optimally modeled.

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II. Literature Overview

Hybrid solar–wind power plants are considered to be a long-term solution for clean renewable energy based electrical energy source. Many types of hybrid power plants are becoming popular in recent years. The most common hybrid power plant is the solar–wind power plant, but there are also many combinations with small hydro and fuel cell power plants. Therefore, many research papers are lately published which consider hybrid power plants. In [3] the authors propose a hybrid solar–wind educational test system in Iowa to supply the load demand of their faculty. The system has a rated power of 12 kW and it is associated with wireless sensors and LabVIEW based monitoring instrumentation systems. A feasibility study of a standalone hybrid solar–wind system for a remote island is shown in [4]. This system also has installed batteries to serve as a backup supply when there is not enough wind and solar energy.

Many of the aforementioned research papers are focused on distributed generation aspect of hybrid solar–wind power plant. Using hybrid solar–wind power plants to supply distant load areas helps the local facility to dodge capital intensive investments in transmission lines. Reference [5] proposes the construction of hybrid solar–wind power plant which would serve for the electrification of rural areas of Nigeria. Reference [6] the authors propose an optimal design of a hybrid solar–wind power plant to supply the local desalination plants in South-Western Asia. Using hybrid solar–wind power plant for that purpose instead of a fossil fuel power plant decreases the price of clean drinking water in that case.

Small hybrid solar–wind power plants can be used to supply small loads like traffic lights, measuring units etc. Reference [7] shows a proposed design and implementation of a hybrid solar–wind energy tower. As it is shown in that paper the hybrid energy tower has a higher total efficiency from a diesel generator system with same annual energy production. The modeling and dynamic simulation of a standalone solar–wind power plants are shown in [8] where authors use an interesting approach on battery charging and supplying the demanded energy. Many research papers on hybrid solar–wind power plants are based on the optimization of those power plants. Since it is needed to produce as much as possible energy without critically disturbing the power quality, many papers use different optimization methods for the design of hybrid solar–wind power plants. [2], [9], [10], [11]

The aforementioned power quality disturbances need to be controlled and lowered during the modeling and optimization of the hybrid solar–wind power plants. The effect of solar irradiance on the power quality behavior of grid is shown in [12]. Reference [13] presents the power quality studies and voltage waveform analysis as a common issue in distribution networks with hybrid solar–wind power plants as a distributed source. The power quality disturbances in isolated power systems with hybrid solar–wind power plants are shown in [14].

III. Modeling the Individual Sources

The analyzed model of hybrid power plant in this paper consists of a wind power plant and a photovoltaic power plant. As it is said before, one of the most important goals is to optimize the output power from both power plants. In that case the demand side will be supplied with enough energy in real time.

A. Mathematical model of photovoltaic power generation

The power generated by a photovoltaic power plant depends on two main parameters, the solar irradiation and the ambient temperature as shown in (1).

$$P(t) = \eta A G(t) \tag{1}$$

Where η is the efficiency of photovoltaic generation, A (m^2) is the area of the photovoltaic panels and $G(t)$ is the solar irradiation on the photovoltaic panel (W/m^2).

The efficiency η is related to the ambient temperature as:

$$\eta = \eta_r \left[1 - \beta \left(T_c - T_{cref} \right) \right] \tag{2}$$

η_r is the reference module efficiency and T_{cref} is reference cell temperature in (°C). [9]

B. Mathematical model of wind power generation

The output power of a wind turbine is usually given by (3).

$$P_m(t) = \frac{1}{2} \rho A_b c_P(\lambda, \beta) v_w^3(t) \tag{3}$$

Where c_P is the coefficient of performance of the turbine, which is also often called power coefficient. The area swept by the turbine blades is given by A_b (m^2). The air density is a function of ambient temperature and sea altitude (who have impact on atmospheric pressure) is taken in account as a constant and given by ρ (kg/m^3). The wind speed (m/s) is given by v_w and as it can be seen, the output power from a wind turbine has a cubic dependence.

The tip speed ratio λ is defined as the ratio of the angular rotor speed of the wind turbine to the linear wind speed at the tip of the blades and can be expressed as:

$$\lambda = \frac{\omega_r R}{v_w} \tag{4}$$

Where ω_r is the mechanical angular velocity of the turbine rotor given in (rad/s) and v_w is the wind speed given in (m/s). [15]

The rotational speed n (r/min) and angular speed ω_r are related by (5). [16]

$$\omega_r = \frac{2\pi n}{60} \tag{5}$$

The modeled system uses a variable speed wind turbine (VSWT), and for that type of turbine the coefficient c_P is calculated as shown in (6).

$$c_p(\lambda,\beta) = 0.73\left[\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right] e^{-\frac{18.4}{\lambda_i}} \quad (6)$$

Where λ_i is given by (7).

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.02\beta} - \frac{0.03}{\beta^3 + 1}} \quad (7)$$

IV. Modeling of the Hybrid Solar–Wind Power Plant

Modeling of the hybrid solar–wind power plant has been done in the MATLAB/Simulink software. The hybrid solar–wind power plant is used to supply a consumer area that is also powered from a public power grid.

Figure 1. shows the basic scheme of the proposed hybrid solar–wind power plant that is being analyzed.

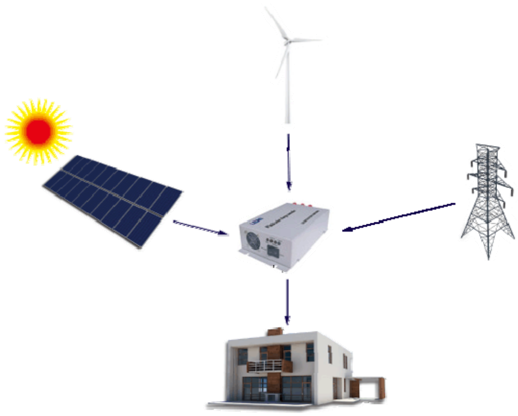

Fig. 1 The basic scheme of the proposed hybrid solar–wind power plant

The photovoltaic modules which are used in the modeling process are SPR-415E-WHT-D with efficiency coefficient of 19.2 %. The nominal output power of one module is 415 (W).

Figure 2. shows the I-V and P-V characteristics of the used photovoltaic modules with three important points: short circuit point, maximum power point and open circuit point.

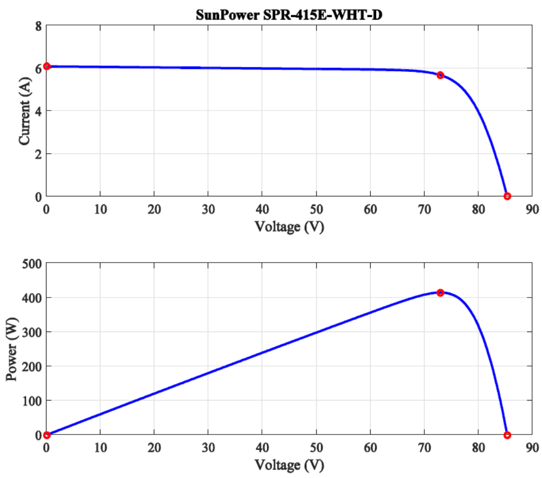

Fig. 2 I-V and P-V characteristics of the used photovoltaic modules

The modeled photovoltaic power plants as a part of the proposed hybrid solar–wind power plant consists of 88 strings with 7 modules connected in series. The maximum power of this photovoltaic source is 250 (kW) which is considered on nominal temperature and solar irradiation. Modeled photovoltaic modules have two input signals, cell temperature and solar irradiation. Since the photovoltaic power plants are a DC source the photovoltaic part of the hybrid power plant is connected with the grid through power electronic devices. The used convertor is a IGBT bridge who with the use of pulse width modulation in converting the DC to AC. Although being used in many cases, the DC to DC convertor haven't been used in the following model. Since the disturbed waveform of AC voltage after the convertor could cause many problems, capacitors were used as filters lower the voltage distortion.

The modeled wind power plant part of the hybrid solar–wind power plant is based on using a synchronous generator with permanent magnets with full convertor. The nominal output power of the used generator is 2 (MW). The used wind turbine has good characteristics in dynamic situations where the generator seems to be virtually disconnected from the rest of the grid during short circuit situations. The nominal speed of the used wind turbine is 11 (m/s), and that means that for wind speeds from 11 (m/s) to 25 (m/s), the wind turbine should generate nominal power which is 2 (MW). Modeled wind turbine uses the pitch regulation mechanics to control the output power which has a positive impact on the total performance of the wind turbine.

The mentioned full convertor of the used synchronous generator is a AC/DC/AC convertor. As it can be seen, the full convertor is used to express the two times conversion of energy. The AC to DC convertor is a classic diode bridge rectifier, the DC to DC convertor is a Buck/Boost convertor with the DC voltage control and the DC to AC convertor is a current controlled convertor who controls both active and reactive output power. [17]

Figure 3. shows the change of output power P (p.u.), the tip speed ratio coefficient λ and the coefficient of performance of the wind turbine c_P as a function of wind speed.

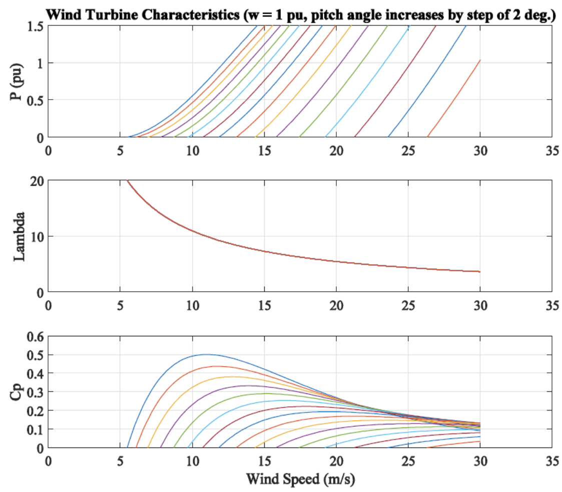

Fig. 3 Change of the output power, tip speed ratio and the coefficient of performance as a function of wind speed

After the modeling of the parts of the hybrid solar–wind power plant is complete, it is needed to model the change of solar irradiation and the wind speed during a single day. The simulation is going to show the behaviour and the impact of hybrid solar–wind power plants on power quality during the 24 hours. The mentioned resource change is explained in previous sections.

Figure 4 shows the change of solar irradiation and wind speed during 24 hours.

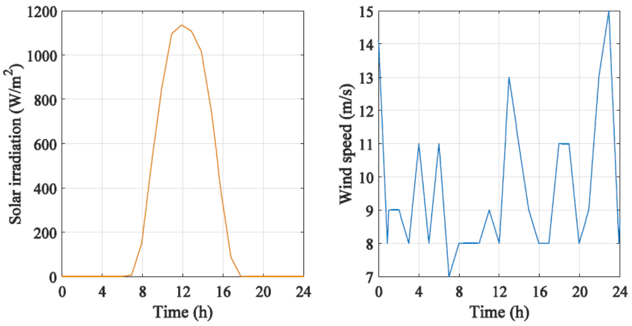

Fig. 4 Daily solar irradiation and wind speed

V. Results and the Impact on Power Quality

In order to analyze the problems of power generation and power quality it is needed to simulate the 24-hours working cycle of a hybrid solar–wind power plant since their work and power generation changes during the day.

Figure 5 shows the daily change of output power and DC voltage of photovoltaic part of hybrid power plant.

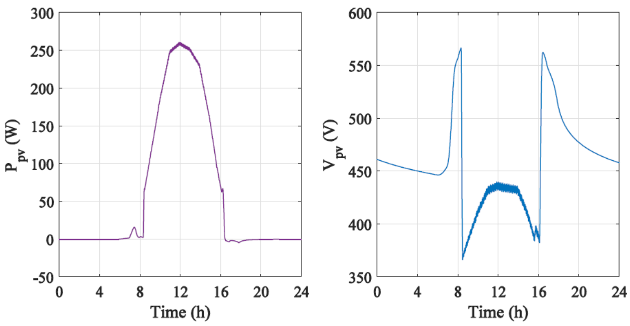

Fig. 5 Daily changes of the active power and voltage of the photovoltaic part of hybrid solar–wind power plant

It can be seen that the active output power from photovoltaic part of hybrid solar–wind power plant almost perfectly follows the daily solar irradiation change. The reason for that is the almost linear dependence between active power and solar irradiation (if the dependence between solar irradiation and panel temperature is neglected). On the other hand, the DC voltage on the connection pins of photovoltaic part of hybrid power plant from the start until the 7th hour of the simulation is the open circuit voltage since the photovoltaic part is disconnected from the rest of the grid due to the security measures. Open circuit voltage slowly increases with the rise of solar irradiation which can be seen in the just before the 7th hour of the simulation. After the photovoltaic part has been connected to the grid, the photovoltaic part of the hybrid solar–wind power plant has a fast drop since the photovoltaic part is no longer in open circuit state. After the photovoltaic power plant has been disconnected again, the DC voltage is again open circuit voltage.

Figure 6 shows the daily change of output power and DC voltage of photovoltaic part of hybrid power plant.

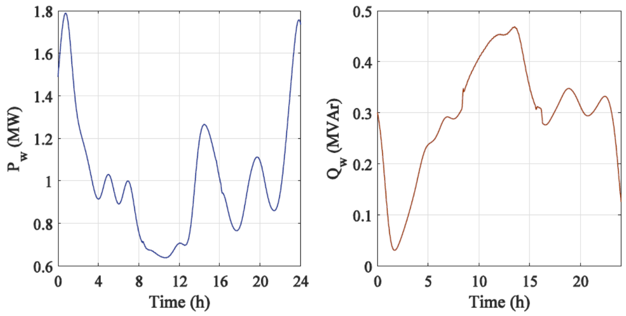

Fig. 6 Daily changes of the active and reactive output power of the wind turbine part of hybrid solar – wind power plant

Since the most of the simulation time, the wind speed is below the wind turbine rated wind speed, it is clear why the production of active wind power is less than the rated power. Just like the connection between solar irradiation and photovoltaic output active power, the before described dependence between the wind speed and the output power can be seen from Figure 6. Due to constant wind speed changes, there is a constant change of power which in turn has an impact on the rest of the results where the fluctuations of the values can be seen.

The consumer area has been modeled with constant power loads which are powered together with hybrid solar–wind power plant and public network.

Figure 7 shows the RMS current value of phase A of the three separate loads.

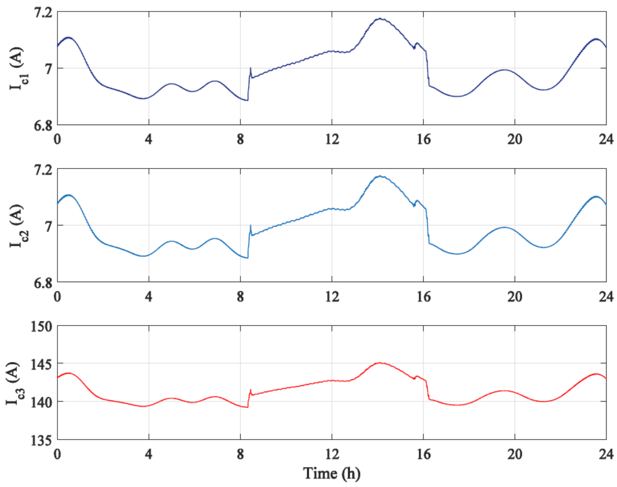

Fig. 7 The RMS current value of the three separate loads

Since the modeled loads have constant power, usually it is expected to have constant load current, but in this case that is not possible. The load connection point voltage is in a close relationship with the generated power from the hybrid solar–wind power plant. Therefore, when the voltage changes due to the power generation change, the load currents also change in order to keep the constant power. A great correspondence of load current with photovoltaic and wind turbine output power can be seen in Figure 7.

Since the photovoltaic part of a hybrid solar–wind power plant switches on and off as the function of solar irradiation, it is necessary to perform an analysis in at least two different moments. At one point, photovoltaic power plant is disconnected from the rest of the grid, in order to preserve equipment lifetime and security measures, and the loads are supplied from wind power plant and public grid. On the other hand, when the solar irradiation goes over the set limit, the loads are supplied from both parts of hybrid solar–wind power plant.

Figure 8 shows the current harmonic spectrum at the load connection point without and with the photovoltaic power plant in use.

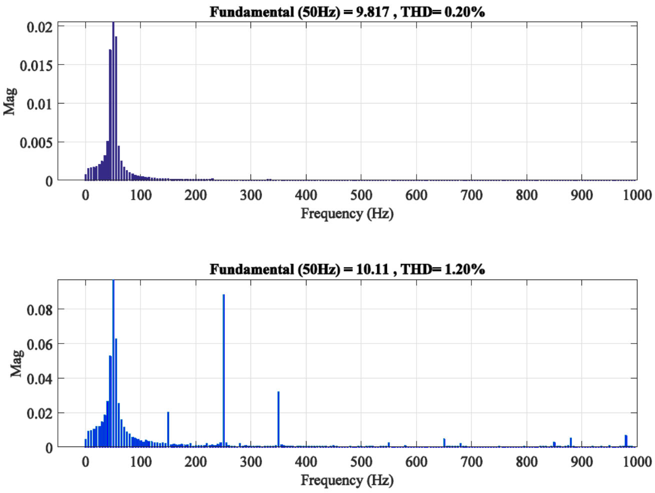

Fig. 8 Current harmonic spectre at the load connection point without and with photovoltaic power plant in use

Figure 8 shows the difference in harmonic distribution in two aforementioned time moments. This is a direct consequence of power electronic devices that convert from DC to AC. In addition to that, total harmonic distortion of currents is also different. When the loads are supplied from both parts of the hybrid solar–wind power plant, the harmonic distortion of the currents is bigger than the situation when the photovoltaic part is disconnected from the rest of the grid.

In addition to possible big problem of supply voltage disturbances, another factor that is being monitored in normative and standards is the total harmonic distortion of supply voltage. Total voltage harmonic distortion (THD), calculated based on all harmonics with ordinal numbers up to 40, must not be higher than 8 % according to the EN 50160, and is calculated using the expression:

$$THD = \sqrt{\sum_{n=2}^{40} (U_n)^2} \qquad (8)$$

where U_n is harmonic ordinal number. [18]

Figure 9 shows the supply voltage harmonic spectrum at the load connection point without and with the photovoltaic power plant in use.

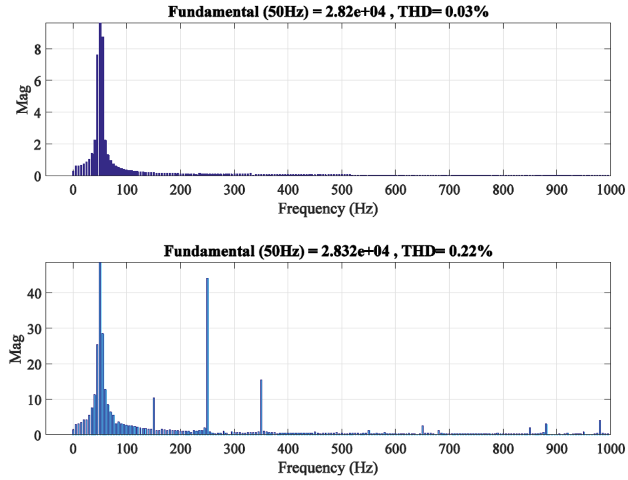

Fig. 9 Supply voltage harmonic spectre at the load connection point without and with photovoltaic power plant in use

As it can be seen, the total harmonic distortion of voltage is in both cases far from the allowed limit.

In addition to the harmonic problems, another power quality problem that appears with the use of hybrid solar–wind power plants are the rapid and slow voltage change due to the wind power plant output power change. It is known that wind speed changes very fast from time to time, therefore, the output power and the voltage at the connection point changes fast, too. It is important to notice that the voltage didn't go outside of allowed ± 10 % change.

Figure 10 shows the voltage change at the connection point of the hybrid solar–wind power plant.

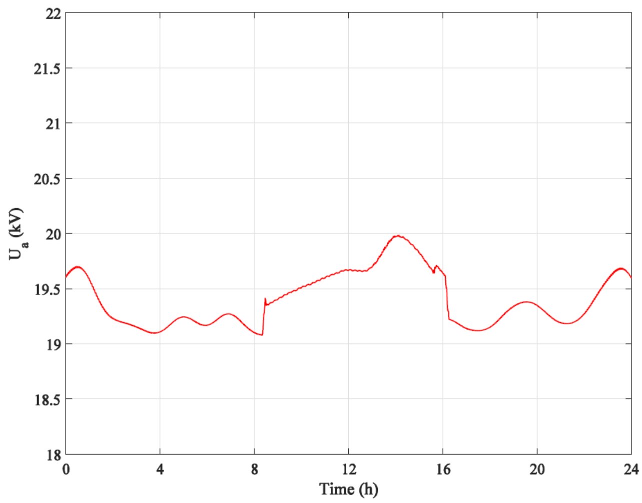

Fig. 10 Voltage change at the hybrid solar – wind power plant connection point

VI. Conclusion

The negative influence on power quality of the dynamics of hybrid solar–wind power plants is clearly visible. The main problem of these power plants is the harmonic emission and it has to be considered. During sunny days, the harmonic emission is bigger than usual and therefore the total harmonic distortion of supply voltage is getting closer to the allowed limit. In these cases, the wind speed needs to be higher, so that the total harmonic disturbances become muted due to high power generation. Another way to annul the harmonic disturbances is to use active filters instead of passive filters which would track load changes and inject the opposite harmonics to annul the generated ones. However, the place of the connection point of hybrid solar–wind power plants is also a vital part in the total connection process since it is known that systems with higher three phase fault power can endure higher harmonic emission. The type of wind generator is also an important factor in the power quality disturbances analysis.

During the modeling of hybrid solar–wind power plants the daily and annual change of solar irradiation and wind speed, needs to be taken in account. Without doing this, the hybrid power plant could cause more damage than expected. These power plants can lower the power losses since they are usually built as distributed energy sources. But, on the other hand, the investor needs to be careful since the wind energy and photovoltaic technology are not a cheap type of energy generation yet. Hybrid solar–wind power plants are a good way to avoid the dependences on non-renewable energy resources like fossil fuel power plants.

The plan for future research is the modeling of autonomous hybrid solar–wind power plants with battery storage and their control and regulation of frequency and voltage. With these power plants, many problems with electricity in third world countries could be solved.

Acknowledgment

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References

[1] N. Rajaković, D. Tasić, *Distributed and industrial power grids*, Belgrade, Serbia, Akademska misao, 2008, pp. 441.

[2] K. Mousa, H. AlZu'bi, A. Diabat, "Design of a Hybrid Solar-Wind Power Plants Using Optimisation," Engineering Systems Management and its Applications (ICESMA), Second International Conference, Sharjah, UAE, May 2010.

[3] R. Pecen, A. Nayir, "Design and Implementation of a 12 kW Wind – Solar Distributed Power and Instrumentation System as an Educational Testbed for Electrical Engineering Technology Students", Modern Electric Power Systems (MEPS), Wroclaw, Poland, 2010.

[4] T. Ma, H. Yang, L. Lu, "A feasibility study of a stand-alone hybrid solar-wind-battery system for a remote island", Article in Applied Energy, ISSN 0306-2619, May 2014.

[5] D. Nnadi & C. Odeh, "Use of Hybrid Solar – Wind Energy Generation for Remote Area Electrification in South – Eastern Nigeria," Article in Journal of Energy in Southern Africa, Vol 25, no. 2, May 2014.

[6] A. Diabat & H. E. S. Fath, "Optimal Design of a Hybrid Solar – Wind Power to Drive a Small Size Reverrse Osmosis Desalination Plant," Article in Desalination and Water Treatment, pp. 3417 – 3427, May 2013

[7] V. Thiruchelvam & G. T. J. Ao, "Design and Implementation of a Hybrid Solar Wind Energy Tower," 2015 IEEE Conference on Control Applications (CCA), Sydney, NSW, pp. 371 – 375, Sept. 2015.

[8] A. M. Dizqah, A. Maheri, K. Busawon, P. Fritzson, "Acasual Modelling and Dynamic Simulation of the Standalone Wind-Solar Plant using Modelica", UKSim 15th International Conference on Computer Modelling and Simulation, 2013.

[9] A. Acakpovi, E. B. Hagan, "Cost Optimization of an Electrical Energy Supply from a Hybrid Solar, Wind and Hydropower plant", Article in International Journal of Computer Applications, Vol. 114, No. 19, ISSN 0975-8887, March 2015.

[10] M. Ghiamy, "Optimal design of a hybrid solar – wind – diesel power system for rural electrification using imperialist competitive algorithm", Article in International Journal of Renewable Energy Research, Vol. 3, No. 2, January 2013.

[11] T. Ma, H. Yang, L. Lu, J. Peng, "Optimal design of an autonomous solar-wind-pumped storage power supply system", Article in Applied Energy, ISSN 0306-2619, May 2014.

[12] M. Patsalides, D. Evagorou, G. Makrides, Z. Achillides, G. Georghiou and others, "The Effect of Solar Irradiance on the Power Quality Behaviour of Grid Connected Photovoltaic Systems", International Conference on Renewable Energies and Power Quality (ICREPQ), Sevilla, Spain, March 2007.

[13] C. D. Dumitru & A. Gligor, "Modeling and Simulation of Renewable Hybrid Power System Using MATLAB/Simulink Enviroment," Scientific Bulletin of the "Petru Maior" University of Targu Mures, Vol 7, no. 2, Jan. 2010.

[14] D. Bica, C. D. Dumitru, "Isolated Hybrid Solar-Wind-Hydro Renewable Energy Systems", InTech, December 2009.

[15] S. Khajuria, J. Kaur, Implementation of Pitch Control of Wind Turbine using Simuling (Matlab), International Journal of Advanced Research in computer Engineering and technology (IJARCET), vol. 1, ISSN 2278-1323, 2012.

[16] S. Masic, *Electrical Machines*, University of Sarajevo, Faculty of Electrical Engineering, Sarajevo 2006.

[17] M. Singh, S. Santoso, Dynamic Models for Wind Turbines and Wind Power Plants, National Renewable Energy Laboratory, The University of Texas at Austin, Texas 2011.

[18] European norme, Voltage Disturbances Standard – EN 50160, 2011.