Local and Central Control of a Wind Farm for Active Power Adjustment

Abdelkarim Masmoudi [*], Achraf Abdelkafi [*‡], Lotfi Krichen [*], Abdelaziz Salah Saidi [**]

[*] University of Sfax, National Engineering School of Sfax, Electrical Systems and Renewable Energies Laboratory (LSEER), BP 1173, Sfax 3038, Tunisia

[**] Department of Electrical Engineering, King Khalid University, Abha. P.O. Box: 394, Abha City P.C.: 61411, Saudi Arabia

[**] University of Tunis El Manar, National Engineering School of Tunis, Electrical Systems Laboratory, Tunisia

(abdelkarim.masmoudi@enetcom.usf.tn, achraf.abdelkafi@enis.tn, lotfi.krichen@enis.tn, asaidi@kku.edu.sa)

[‡]Corresponding Author; Achraf ABDELKAFI, National Engineering School of Sfax, Electrical Systems and Renewable Energies Laboratory (LSEER), BP 1173, 3038, Sfax, Tunisia, Tel.: (+216) 74 274 418 / Fax: (+216) 74 275 595, achraf.abdelkafi@enis.tn

Received: 01.03.2022 Accepted: 02.04.2022

Abstract- The work presented in this paper deals with the active power control in a wind farm based on both central and local control levels. A central supervision unit (CSU) ensures the power coordination between the local supervision units (LSU) of each wind turbine. In the local supervision unit, a power management has been developed in order to adjust the distribution of the farm's production. The main contribution of the developed work is the adjustment of the delivered power by each wind turbine using an additional control of the pitch angle. Consequently, power control flexibility for the wind farm system was established by considering either maximum power point tracking (MPPT) mode or limited power point tracking (LPPT) mode. Therefore, the LSU inside each wind turbine control effectively coordinates with the power distribution received from the CSU according to the wind farm available power. Simulation results presented in this paper have shown the good performance and the high stability of the proposed supervision strategy for the considered wind farm.

Keywords Wind farm, pitch control, power balance, central and local control, MPPT, LPPT.

Nomenclature

$n = 3$	number of wind turbines in the wind farm
V_i	wind speed applied to each wind turbine , (m/s)
ρ	air density, (kg/m^3)
R	blade radius, (m)
C_{pi}	power coefficient of the wind turbine i ; $i \in \{1,2,3\}$
λ_i	tip-speed ratio
β_i	pitch angle, (°)
$\Delta\beta_i$	Additional pitch angle, (°)
β_{it}	total pitch angle, (°)
Ω_{ti}	blade rotational speed, (rad/s)
Ω_{mi}	mechanical speed, (rad/s)
P_{gi}	wind turbine i generated power, (W)
P_{gi_ref}	wind turbine i reference generated power, (W)
$P_{gi-MPPT}$	wind turbine i MPPT power, (W)
$P_{gi-LPPT}$	wind turbine i LPPT power, (W)
P_G	power generated by the wind farm, (W)
P_L	load power demand, (W)

1. Introduction

Most of the energy consumed today comes from the use of fossil fuels such as petroleum, coal, natural gas. The consumption of these sources gives rise to gas emissions and therefore an increase in pollution. The additional danger is that excessive consumption of the stock of natural resources reduces the reserves of this type of energy for future generations. It is estimated that world reserves will be exhausted if production and consumption are not drastically changed [1,2].

Faced with the demand for electricity, which is still growing today, and far from the use of polluting fossil fuels, several countries have turned to new green energies known as "renewable". Among them, wind power and photovoltaic energy signal a faster development in the world and are gradually taking an important place in the electricity market [2]. The competitiveness of wind energy and its increasingly competitive cost with conventional means of production affects the use of this type of energy for the electrification of isolated sites and the connection to the electrical network. In order to improve the electrical power supplying, wind farms made up of several wind turbines are the most suitable solution used by many countries [3]. The majority of these farms are controlled to provide their maximum power with the fault ride through capability [4].

Several recent research works in the field of wind farm are directed towards the design of supervision algorithms with the aim of an optimal power distribution on the various wind turbines. In Refs. [5-8], authors worked on the requirements imposed by the transmission system operator (TSO) for the wind farms integration to the grid without affecting safety and stability. To increase the controllability of the power system, various studies have dealt with the techniques of supervision and control of wind farms such as the control of active and reactive power in Refs. [9-14], the voltage control in Refs. [15-17], and the frequency control in Refs. [18-21]. The studies detailed in Refs. [22-24], present several autonomous hybrid energy systems based on the kinetic energy of the wind. Energy management and supervision strategies were developed in order to show the interest of integrating storage systems in autonomous applications for improving the quality of the energy produced. In Refs. [25,26] authors show the influence of controlling the pitch angle on the mechanical and the electrical performance of a wind farm with relation to the wind turbine speed and power.

In this context, the work presented in this paper is concentrated on the central and local control of the active power production in a wind farm. The wind farm studied is a combination of three wind subsystems connected to the common DC bus which injects the energy generated into the autonomous grid through a DC/AC converter and a filter. Each wind subsystem consists of a horizontal axis wind turbine driving a permanent magnet synchronous generator (PMSG). MPPT control and energy transfer from each turbine in the farm is provided through an AC/DC converter.

The connection of wind farms to the autonomous grid is conditioned by active power requirements imposed by the loads connected in the implementation site. Indeed, the majority of wind farms connected to the autonomous grid are controlled either to generate their maximum power or to provide a predefined active power to meet the power demanded by the loads. The strategy investigated in this work consists of exchanging an information flow between the electrical network and the wind farm to design an adequate power distribution. In order to control the active power transferred to the implementation site, two local and central supervision units of the wind farm were set up. The CSU will transfer the necessary information to each LSU which controls of the corresponding wind turbine according to a supervision algorithm. An additional control of the pitch angle of each turbine ensures the production adjustment according to the reference powers received at the input of each LSU.

The remainder of this paper is organized in four sections. Section 2 presents the wind farm configuration with a detailed description of the CSU and the LSU. The development and the implementation of the proposed wind farm power management strategy are evoked in section 3. Simulation results and some conclusions of this work are detailed and described in sections 4 and 5, respectively.

2. Wind farm configuration

Fig. 1 illustrates a general description of the studied wind farm. This structure is made up of three variable speed wind turbine generators with a total nominal power of 6kW. The control of the wind farm is ensured by two supervision units. The first one is a central supervision unit which instantly manages the wind farm power production according to the load variation and the available power in each wind turbine. The second one is the local supervision unit which receives the information about the reference power from the CSU in order to adapt the production of each wind turbine.

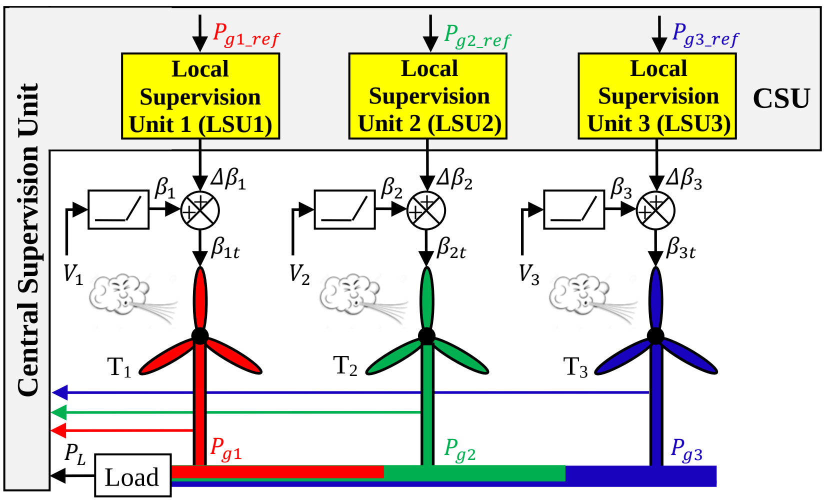

Fig. 1. Wind farm structure.

2.1. Central supervision unit description

The central supervision unit is a coordinator between the three wind turbines and the load. The main purpose of the CSU is the control of the active power generated by the wind farm according to a variable demand of the load power. By adopting a proportional power distribution, the CSU receives as input the power request "P_L" and the wind farm production "P_G" in order to send the power references to each wind tubine.

2.2. Local supervision unit description

Each wind turbine has its own local supervision unit. Two operation modes are considered. The first mode is the maximum power point tracking (MPPT) operation which consists in extracting all the available power from the wind turbine. The second mode corresponds to an operation below the MPPT. This mode is activated when it is necessary to limit the power production according to the load demand. The active power generated by the farm should not exceed "P_L", even with the availability of an excess power. The proposed idea to limit the power generated from the wind turbine "i" to the reference calculated by the CSU consists in increasing the pitch angle "β_i" by an additional term "$\Delta\beta_i$" in proportion with the excess power. Consequently, the production of each wind generator is adapted to the load demand and power balance is guaranteed.

3. Wind farm power management strategy

The proposed flowchart for the wind farm energy supervision is illustrated in Fig. 2. In this structure, it was considered that consumers impose a variable demand on the load power. The wind farm power production is directly related to the three wind speed profiles.

At first, the total generated power "P_G" is tested and compared to the load power demand "P_L".

In the case where "P_G" is less than "P_L", the three turbines T_1, T_2 and T_3 are controlled in MPPT mode in order to deliver their maximum power. Otherwise, each turbine is tested individually. Indeed, if the power generated by a wind turbine "i" is less than the third of the power requested by the loads, this wind turbine is still controlled in the MPPT mode. In the other case, the reference power in which the corresponding wind turbine should be limited is determined. This reference power corresponds to the difference between the power requested by the loads and the sum of the powers generated by the other wind turbines "$\sum_{j=1}^{n} P_{gj}$" according to the following equation:

$$P_{gi\_ref} = \left(P_L - \sum_{j=1}^{n} P_{gj} \right) + P_{gi} \quad (1)$$

If the power "P_{gi}" is less than or equal to the reference power "P_{gi_ref}", the pitch angle "β_{it}" of the wind turbine "i" receives only the angle "β_i" which is proportional to the wind speed. When the wind speed exceeds its nominal wind value, a control of this angle will maintain the mechanical speed as a protection from any possible damage. In the other case, when the power "P_{gi}" is greater than the reference power "P_{gi_ref}", the LSU will change the wind turbine operation mode from the MPPT to the LPPT according to the reference power provided from the CSU. For the affected wind turbine, an additional pitch angle "$\Delta\beta_i$" is instantaneously calculated in order to give an exact tracking of the desired power. The increase by the term "$\Delta\beta_i$" of the pitch angle leads to a decrease in the power coefficient "C_{pi}" of the wind turbine "i" and subsequently a reduction in the generated power "P_{gi}".

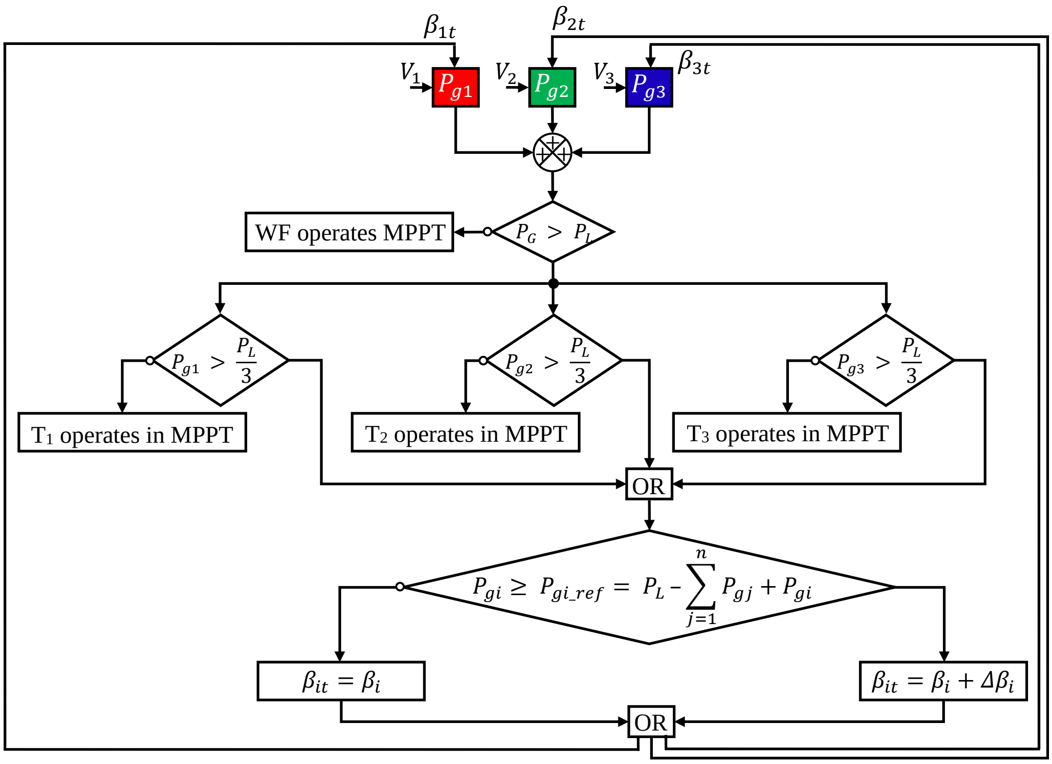

Fig. 2. Wind farm control strategy.

The power coefficient expression used in this work has been approximated by the following expression given by references [27,28]:

$$C_{pi}(\lambda_i, \beta_i + \Delta\beta_i) = 0.53\left(151\left(\frac{1}{\lambda_i - 0.02(\beta_i + \Delta\beta_i)} - \frac{0.003}{(\beta_i + \Delta\beta_i)^3 + 1}\right) - 0.58(\beta_i + \Delta\beta_i) - 0.002(\beta_i + \Delta\beta_i)^{2.14} - 10\right) e^{-18.4\left(\frac{1}{\lambda_i - 0.02(\beta_i + \Delta\beta_i)} - \frac{0.003}{(\beta_i + \Delta\beta_i)^3 + 1}\right)} \quad (2)$$

The coefficient "C_{pi}" depends on the pitch angle "$\beta_i + \Delta\beta_i$" and the tip speed ratio "λ_i" .

$$\lambda_i = \frac{R\Omega_{ti}}{V_i} \quad (3)$$

where "R" is the blade length and "Ω_{ti}" is the blade rotational speed.

Fig. 3 illustrates the evolution of the power coefficient for different values of the pitch angle. It is observed that the increase in the pitch angle causes a decrease in the power coefficient.

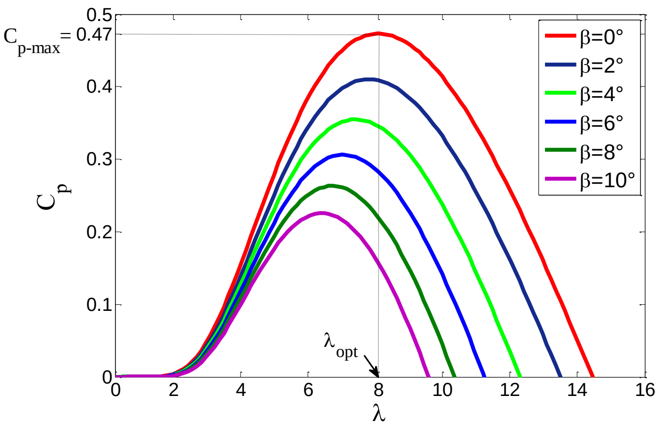

Fig. 3. "C_p" versus "λ" curves for different pitch angle values.

The power generated by each wind turbine is written as follows [27,28]:

$$P_{gi} = \frac{1}{2}\rho\pi R^2 V_i^3 C_{pi}(\lambda_i, \beta_i + \Delta\beta_i) \quad (4)$$

where "ρ" is the air density and "V_i" is the wind speed.

The wind turbine parameters are given in Table 1.

Table 1. Wind turbine parameters.

Parameter	Symbol	Value
air density	ρ	1.22 kg/m^3
blade radius	R	1.35 m
rated wind speed	V_n	10.66 m/s
maximum power coefficient	C_{p_max}	0.47
optimal tip-speed ratio	λ_{opt}	8
nominal power	P_n	2 kW

By applying the proposed control strategy detailed in Fig. 2, each wind turbine can operate in "MPPT" or "LPPT" mode. The different cases that could occur are shown in Table 2.

Table 2. Turbine operation modes.

Case	$P_G - P_L$	T_1	T_2	T_3
1	< 0	MPPT	MPPT	MPPT
2	> 0	MPPT	MPPT	LPPT
3	> 0	MPPT	LPPT	MPPT
4	> 0	MPPT	LPPT	LPPT
5	> 0	LPPT	MPPT	MPPT
6	> 0	LPPT	MPPT	LPPT
7	> 0	LPPT	LPPT	MPPT
8	> 0	LPPT	LPPT	LPPT

4. Simulation results and discussion

The proposed control strategy was tested during 300 s on a wind farm made up of three wind turbines using Matlab/Simulink software. In order to give a clear presentation of the simulation results, the power demanded by the load has been chosen in the form of constant levels every 50 s as shown in Fig. 4. For the same reason, the wind turbines has been subjected to three different wind profiles which are purely theoretical with different variation levels according to the power demand time changes as depicted in Fig. 5. This choice will facilitate the validation of the proposed power management strategy for all possible cases.

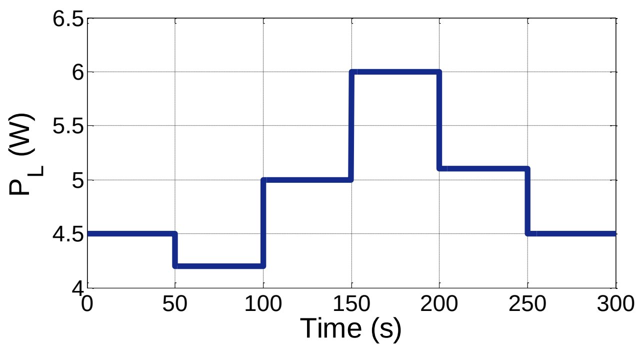

Fig. 4. Power demanded by loads.

The three wind turbines are dimensioned for a nominal power of "$P_n = 2\ kW$" with a nominal wind speed of "$V_n = 10.66\ m/s$". Beyond this wind speed, it is necessary to mechanically protect each turbine in the wind farm by the pith control mechanism. Fig. 6 shows the pitch angle evolution of each turbine. It is observed that for wind speeds greater than "V_n", the regulation system limit the mechanical speed and the nominal power of each wind turbine to their nominal values "$\Omega_{mi} = 157\ rad/s$" and "$P_{gi} = 2\ kW$", respectively.

Each wind turbine has its own LSU which will activate the operating mode "MPPT" corresponding to the value "0" or the power limitation mode "LPPT" which corresponds to the value "1" as shown in Fig. 7.

It is observed that according to the proposed algorithm, four operating cases in the wind farm are possible:

- Case 1: The three wind turbines operate in MPPT mode in order to provide maximum active power to the loads.
- Case 2: Only one wind turbine is controlled in LPPT mode and two other remain in the MPPT mode.
- Case 3: Two wind turbines are controlled in LPPT mode and the third one remain in MPPT mode.
- Case 4: The three wind turbines operate in LPPT mode.

All these cases are well verified for every load level variation.

For the LPPT mode a specific term "$\Delta\beta_i$" corresponding to the wind turbine "i" is calculated instantaneously according to the desired limitation as illustrated in Fig. 8. The evolution of "$\Delta\beta_i$" depends on the reference power calculated in the CSU and send to the LSU. The variation of the total pitch angle "β_{it}" influences the performance of each wind turbine, and more precisely the power coefficients "C_{pi}" as shown in Fig. 9. "β_{it}" and "C_{pi}" are two inversely proportional quantities. Increasing the angle "β_{it}" causes a decrease in "C_{pi}" and vice versa.

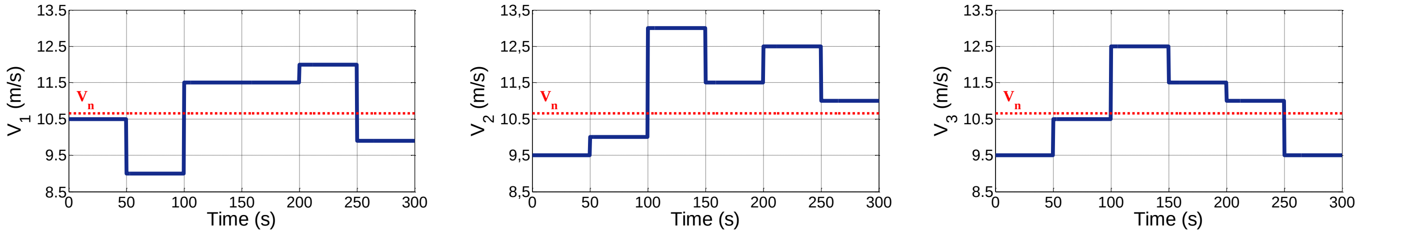

Fig. 5. Wind profiles.

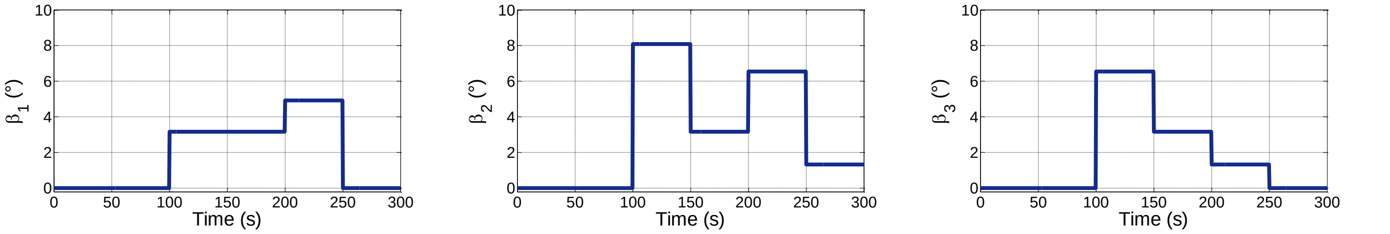

Fig. 6. Pitch angles "β_1", "β_2" and "β_3".

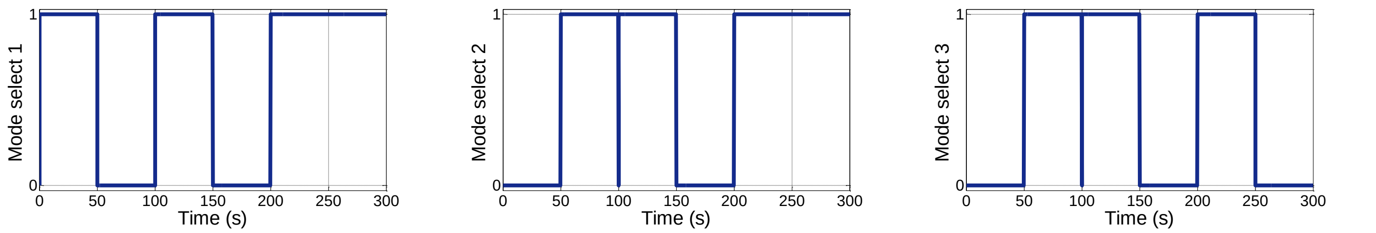

Fig. 7. Wind turbine operating modes.

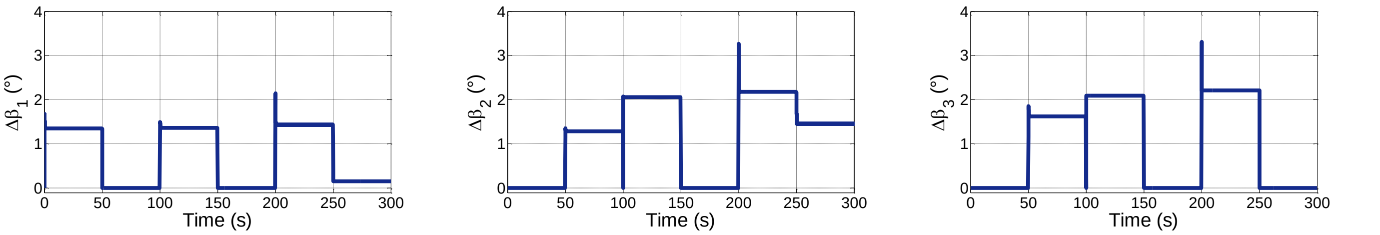

Fig. 8. Additional pitch angles "$\Delta\beta_1$", "$\Delta\beta_2$" and "$\Delta\beta_3$".

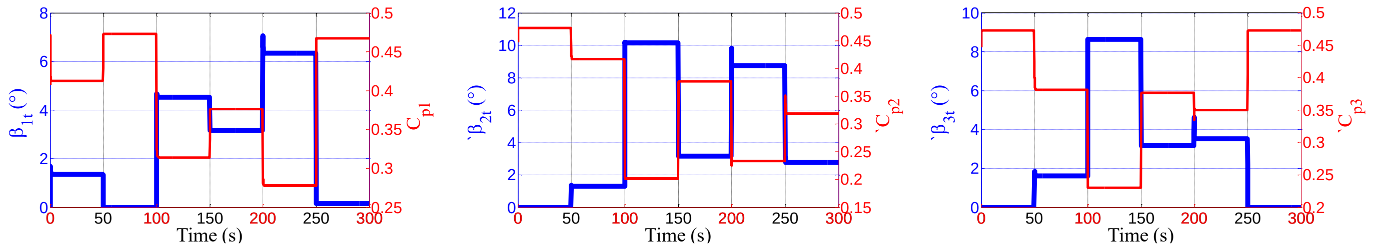

Fig. 9. Pitch angles and power coefficients evolution.

The power requested by the loads is transmitted from the CSU to the LSU as a reference power to the three wind turbines. The main objective of the CSU is to control the total active powers of the wind farm according to variable energy demand. In order to make a comparison between the available and the generated power, Fig. 10 shows the two operating modes MPPT and LPPT for each wind turbine. Effectively, it should be noted that the LPPT power of each wind turbine "$P_{gi-LPPT}$" follows the MPPT power "$P_{gi-MPPT}$" in the case where "$\Delta\beta_i = 0$". In the case of an additional control of the pitch angle when "$\Delta\beta_i \neq 0$", each turbine operates below its maximum capacity in order to adapt the production to the required power which proves the effectiveness of the proposed management strategy.

The simulation results in the interval [0,50s] show that the turbine "T_1" is driven to limit production while the two other turbines "T_2" and "T_3" are driven to generate maximum power. In the intervals [50,100s] and [250,300s], two wind turbines are subject to the LPPT control while the other one is controlled in the MPPT mode since its corresponding power does not exceed the third of the required power. During the intervals [100,150s] and [200,250s], the three wind turbines are controlled in the LPPT mode while during the interval [150,200s] the three wind generators are controlled in the MPPT mode. All possible cases are tested according to the available and the requested power in order to prove the efficiency and the power tracking rapidity of the proposed energy management algorithm.

The power production limitation of each wind turbines is directly related to the decrease in the power coefficient "C_{pi}" as shown in Fig. 11. The increase in "β_i" by "$\Delta\beta_i$" causes a decrease in "C_{pi}". Each wind turbine is mechanically protected by limiting the rotational speed to the nominal speed "$\Omega_{ni} = 157\ rad/s$". Fig. 12 shows the decrease in the mechanical speed "Ω_{mi}" when increasing the angle "β_i" by "$\Delta\beta_i$". Fig. 13 represents the wind farm power balance. It is clear that the total power generated by the farm perfectly follows the power demanded by the loads which confirm the proposed control strategy effectiveness.

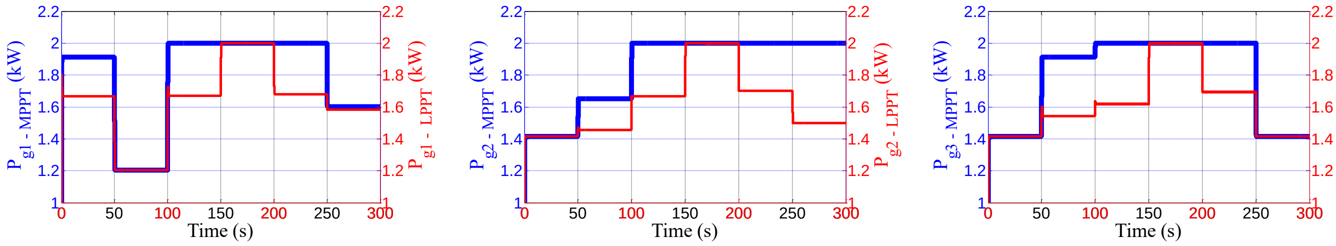

Fig. 10. Wind turbine powers.

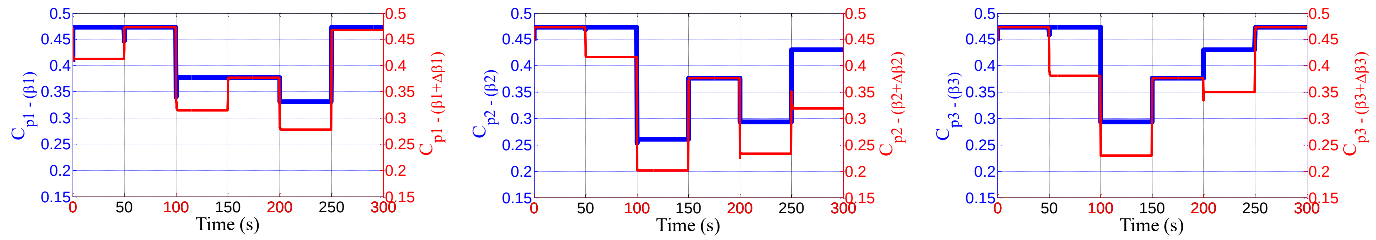

Fig. 11. Effect of "β_i" and "$\beta_i + \Delta\beta_i$ variations on the power coeffficient

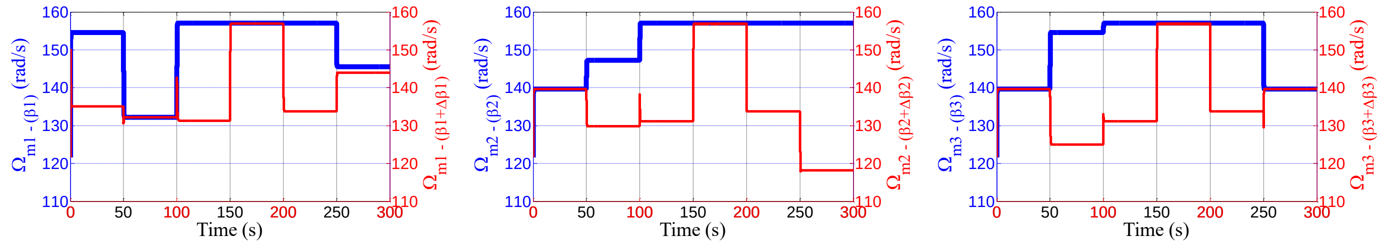

Fig. 12. Wind turbines rotational speed.

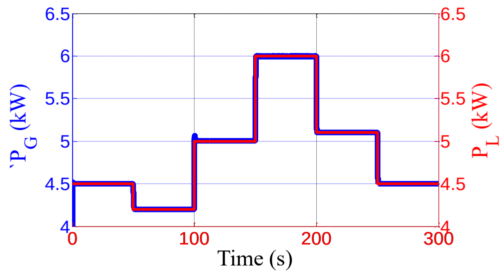

Fig. 13. Generated and required power.

5. Conclusion

The work presented in this paper relates to the active power management of a small wind farm supplying an isolated site. Central and local supervision units were carried out by adopting an adequate algorithm based on a complementary control of the pitch angle of each wind turbine. The proposed management method coordinates the wind farm power distribution and correlates production with consumption. It has been found that by controlling each wind turbine separately using the LSU, the power management flexibility and the balance between consumption and production are well enhanced. In addition the pitch control mechanism will be improved in term of lifespan and robustness. The simulation results were presented in order to show the validity of the supervision algorithm and also to confirm the advantages of the proposed method.

Acknowledgement

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Research Groups Program under grant number (R.G.P.2/81/43).

References

[1] E. R. A. Larico, "Wind energy potential by the weibull distribution at high-altitude peruvian highlands, International Journal of Smart Grid, https://doi.org/10.20508/ijsmartgrid.v5i3.199.g154, Vol. 5, No. 3, pp. 114-120, 2021.

[2] F. A. Khan, N. Pal, and S. H. Saeed, "Review of solar photovoltaic and wind hybrid energy systems for sizing strategies optimization techniques and cost analysis methodologies", Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2018.04.107, vol. 92, pp. 937-947, 2018.

[3] C. Jung, and D. Schindler, "A global wind farm potential index to increase energy yields and accessibility", Energy, https://doi.org/10.1016/j.energy.2021.120923, vol. 231, pp. 120923, 2021.

[4] R. Toujani, A. Abdelkafi, and L. Krichen, "Contribution to the Modeling, Control and Dynamic Management of an Autonomous Wind Farm using a Fuel cell and a Super-capacitor", International Journal of Renewable Energy Research, https://doi.org/10.20508/ijrer.v11i4.12580.g8360, vol. 11, pp. 2045-2056, 2021.

[5] S. M. Muyeen, H. M. Hasanien, and A. Al-Durra, "Transient stability enhancement of wind farms connected to a multi-machine power system by using an adaptive ANN-controlled SMES", Energy Conversion and Management, https://doi.org/10.1016/j.enconman.2013.10.039, vol. 78, pp. 412-420, 2014.

[6] I. M. de Alegría, J. Andreu, J. L. Martín, P. Ibañez, J. L. Villate, and H. Camblong, "Connection requirements for wind farms: A survey on technical requierements and regulation", Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2006.01.008, vol. 11, pp. 1858-1872, 2007.

[7] A. Q. Al-Shetwi, M. A. Hannan, K. P. Jern, M. Mansur, and T. M. I. Mahlia, "Grid-connected renewable energy sources: Review of the recent integration requirements and control methods", Journal of Cleaner Production, https://doi.org/10.1016/j.jclepro.2019.119831, vol. 253, pp. 119831, 2020.

[8] H. Zong, J. Lyu, X. Cai, C. Zhang, M. Molinas, and F. Rao, "Accurate aggregated modelling of wind farm systems in modified sequence domain for stability analysis", Electric Power Systems Research, https://doi.org/10.1016/j.epsr.2019.105928, vol. 175, pp. 105928, 2019.

[9] F. M. Ebrahimi, A. Khayatiyan, and E. Farjah, "A novel optimizing power control strategy for centralized wind farm control system", Renewable Energy, https://doi.org/10.1016/j.renene.2015.07.101, vol. 86, pp. 399-408, 2016.

[10] A. D. Hansen, P. Sørensen, F. Iov, and F. Blaabjerg, "Centralised power control of wind farm with doubly fed induction generators", Renewable Energy, https://doi.org/10.1016/j.renene.2005.05.011, vol. 31, pp. 935-951, 2006.

[11] F. G. Llistuella, A. Sumper, F. D. González, and S. G. Arellano, "Flicker mitigation by reactive power control in wind farm with doubly fed induction generators", International Journal of Electrical Power and Energy Systems, https://doi.org/10.1016/j.ijepes.2013.09.016, vol. 55, pp. 285-296, 2014.

[12] W. Liao, P. Li, Q. Wu, S. Huang, G. Wu, and F. Rong, "Distributed optimal active and reactive power control for wind farms based on ADMM", International Journal of Electrical Power and Energy Systems, https://doi.org/10.1016/j.ijepes.2021.106799, vol. 129, pp. 106799, 2021.

[13] R. Tang, B. Luo, X. Deng, and Y. Shen, "Research on Reactive Power and Voltage Control for Wind Farm Based on coordinate control of DFIGs and SVG", Procedia Computer Science, https://doi.org/10.1016/j.procs.2020.07.066, vol. 175, pp. 460–467, 2020.

[14] J. Tavoosi, A. Mohammadzadeh, B. Pahlevanzadeh, M. B. Kasmani, S. S. Band, R. Safdar, and A. H. Mosavi, "A machine learning approach for active/reactive power control of grid-connected doubly-fed induction generators", Ain Shams Engineering Journal, https://doi.org/10.1016/j.asej.2021.08.007, vol. 13, pp. 101564, 2022.

[15] W. Jiao, Q. Wu, S. Huang, and J. Chen, "Decentralized voltage control of wind farm based on gradient projection method", International Journal of Electrical Power and Energy Systems, https://doi.org/10.1016/j.ijepes.2020.106308, vol. 123, pp. 106308, 2020.

[16] C. D. Sanahuja, I. P. Alós, and R. V. Albalate, "Robust local controllers design for the AC grid voltage control of an offshore wind farm", IFAC-PapersOnLine, https://doi.org/10.1016/j.ifacol.2020.12.1910, vol. 53-2, pp. 12751-12756, 2020.

[17] P. Cartwright, L. Holdsworth, J. Ekanayake, and N. Jenkins, "Co-ordinated voltage control strategy for a doubly-fed induction generator (DFIG)-based wind farm", IET Proceeding, generation, transmission and distribution, https://doi.org/10.1049/ip-gtd:20040581, vol. 151, pp. 495-502, 2004.

[18] H. Badihi, Y. Zhang, and H. Hong, “Active power control design for supporting grid frequency regulation in wind farms”, Annual Reviews in Control, https://doi.org/10.1016/j.arcontrol.2015.09.005, vol. 40, pp. 70-81, 2015.

[19] M. Dreidy, H. Mokhlis, and S. Mekhilef, “Inertia response and frequency control techniques for renewable energy sources: A review”, Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2016.11.170, vol. 69, pp. 144-155, 2017.

[20] G. Lalor, A. Mullane, and M. O'Malley, “Frequency control and wind turbine technologies”, IEEE Transaction on power system, https://doi.org/10.1109/TPWRS.2005.857393, vol. 20, pp. 1905-1913, 2005.

[21] T. Kaneko, A. Uehara, T. Senjyu, A. Yona, and N. Urasaki, “An integrated control method for a wind farm to reduce frequency deviations in a small power system”, Applied Energy, https://doi.org/10.1016/j.apenergy.2010.09.024, vol. 88, pp. 1049-1058, 2011.

[22] K. Kavadias, and P. Triantafyllou, “Wind-Based Stand-Alone Hybrid Energy Systems”, Reference Module in Earth Systems and Environmental Sciences, https://doi.org/10.1016/B978-0-12-819727-1.00162-X, October 2021.

[23] F. E Lamzouri, E. M. Boufounas, and A. ElAmrani, “Efficient energy management and robust power control of a stand-alone wind-photovoltaic hybrid system with battery storage”, Journal of Energy Storage, https://doi.org/10.1016/j.est.2021.103044, vol. 42, pp. 103044, 2021.

[24] P. García, J. P. Torreglosa, L. M. Fernández, and F. Jurado, “Optimal energy management system for stand-alone wind turbine/photovoltaic/hydrogen/battery hybrid system with supervisory control based on fuzzy logic”, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2013.08.106, vol. 38, pp. 14146-14158, 2013.

[25] Y. Jin, P. Ju, C. Rehtanz, F. Wu, and X. Pan, “Equivalent modeling of wind energy conversion considering overall effect of pitch angle controllers in wind farm”, Applied Energy, https://doi.org/10.1016/j.apenergy.2018.03.180, vol. 222, pp. 485-496, 2018.

[26] A. Abdelkafi, and L. Krichen, “New strategy of pitch angle control for energy management of a wind farm”, Energy, https://doi.org/10.1016/j.energy.2011.01.021, vol. 36, pp. 1470–1479, 2011.

[27] A. Masmoudi, A. Abdelkafi, and L. Krichen, “Electric power generation based on variable speed wind turbine under load disturbance”, Energy, https://doi.org/10.1016/j.energy.2011.05.047, vol. 36, pp. 5016–5026, 2011.

[28] J. G. Slootweg, S. W. H de Haan, H. Polinder, and W. L. Kling, “General model for representing variable speed wind turbines in power system dynamics simulations”, IEEE Transactions on Power Systems, https://doi.org/10.1109/TPWRS.2002.807113, vol. 18, pp. 144-151, 2003.