Centralized Active Power Control (CAPC) of PMSG Wind Power Plant for Normal and Frequency Contingency operation

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Abstract— *Wind power plants with Permanent Magnet Synchronous Generators (PMSG) employ full scale back to back converter that totally isolates the rotating system of the wind power plant from the electrical network. Therefore, there is no inertial contribution from wind power plant for primary frequency regulation. While the produced power of a WPGS is based on wind speed operating regimes, this power can be transiently increased with proper control action of the power electronics converter on the generator side. It is essential to design a centralized controller that manages the wind output power during normal operation mode, and that can be switched to the frequency contingency mode to support the network frequency. For normal operation mode, this paper proposes an adjustable controller with a dual objective of energy maximization and loading exertion minimization. For frequency contingency mode a transient active power control algorithm is proposed in order to imitate the response of a conventional synchronous generator. This algorithm uses an additional dual torque controller with one loop for the emulated inertia, and the other for the droop control. Simulations using MATLAB/Simulink were performed under different wind speeds, taking account of the wind aerodynamics to prove the efficacy of the suggested controllers.*

Key words: *Centralized Active Power Control (CAPC), Emulated inertia, Droop control.*

1. Introduction

In modern smart grids, the need for more green energy systems is increasing in order to replace conventional power plants. Increasing the share of wind energy in the global energy market has led to a growing interest in the use of wind power systems to participate in the control of the frequency of the power grid [1], [2]. Only conventional fossil fuel based power plants maintained balance between the produced power and the consumed power during a frequency disturbance while wind farms used to be disconnected by frequency relays and the Rate of Change of Frequency (ROCOF) relays [3], [4]. Most modern wind energy systems are using Variable Speed Wind Turbines (VSWT), in order to maximize power extraction capability. Many research efforts have addressed the issue of optimizing the power extracted from wind energy conversion systems based on Doubly Fed induction Generators (DFIG) which is partly connected to the grid, such as in [5], and [6]. Permanent Magnet Synchronous Generator (PMSG) VSWT are mechanically disengaged from the power grid frequency and do not take part in the frequency adjustment that is available by ordinary power plants [1], [2].

With the excess level of wind power in the electric network, the problem of reduced electric network inertia is getting serious for network operators, with the fluctuation of wind power due to the changing operating conditions [7],[8]. Therefore, there is a growing interest in investigating the capability of the PMSG VSWT to take part in the primary frequency adjustment of the network, which involves the transient variation of active power production for the duration of the frequency disturbance. This capability is known as Active Power Control (APC) [1]. Grid codes such as the European Network of Transmission System Operators for Electricity (ENTSO-E) proposed requirements for wind farms for secure integration with the transmission networks to concentrate on taking part in the frequency adjustment through APC [9]. While the power production of a VSWT is dependent upon the wind speed operating regimes, the produced power of the generator can be transiently increased subsequent to a frequency drop by eliciting the kinetic energy stored in the revolving cluster of the PMSG VSWT wind farm [10].The contribution of wind farms in frequency adjustment is limited to the essential frequency [11], [12]. In [2], a review of the APC methods for the essential or the primary frequency adjustment was introduced. The virtual inertial response was the most widely used method. That method focused on producing the frequency regulation capability intrinsically by adjusting the controller of the Generator Side Converter (GSC).

In literature, the virtual inertial response of the VSWT was performed using different strategies as discussed in [13]-[18]. Those strategies are mainly, a temporary over production, and a synthetic inertia. In research work as in [13]-[15] the temporary over production strategy was addressed. In [11] the potency of a Doubly Fed Induction Generator (DFIG) VSWT for providing temporary additional active power output was studied. This method was based on using an overproduction function that adjusts the power reference value by adding an extra value to the previous value. In [14], a fast large power surge from the stored Kinetic Energy (KE) was delivered based on the sum of the overproduction power values of each VSWT in the wind farm. In [15] the same principle is applied by using the merit of the fast power injection potency of the VSWT, with the ability to set a new power output within practical limits. That method did not make VSWT imitate the behaviour of conventional synchronous generators which are coupled straightway to the grid. In research work as in [16] and [17] the synthetic inertia method was discussed which was based on variations in the measured network frequency. In [16], and [17] the system frequency derivative was used to emancipate the stockpiled kinetic energy in the VSWT revolving cluster under varying wind speeds. The released VSWT inertia within network reduced the rate of variation of frequency, yet other conventional power plants boosted their power production out of the governor operation. In [18], droop control, which depends on the frequency deviation from the set point, was presented as an alternate to the artificial inertia design. It was also stated that the differentiation of the frequency for the inertia response gave rise to a noise signal which may cause oscillations in the VSWT output power. However, this should not be a problem when using a filter in the functional application.

The primary frequency control in the prevalent power plants occurs in two steps, the inertial step, and the primary step. The inertial step promptly comes after the frequency disturbance situation (5-10 sec) [19]. It depends on the natural inertia of the big synchronous machines, where the generator speed decelerates in response to the abrupt load rise or absence of generation. The primary step usually occurs in (20-30 sec) following the frequency event [19], [20]. It depends on the generator governors to stabilize the frequency drop.

In this paper a VSWT centralized APC strategy is proposed to address both normal operation mode and frequency contingency mode of wind farm operation. The proposed centralized strategy is adaptive to operate with different wind speed regimes and to be able to return to normal mode operation without causing system instability. The contributions of the paper are mainly:

- In normal operation mode, a realistic operating scenario of a wind turbine is realized by considering the wind turbulence and the shear effects. The controller in this case decides adaptively the output power based on the wind turbine mode of operation (partial or full load), which mainly depends upon the wind speed profile.
- In frequency contingency mode, the proposed controller is used for supporting primary frequency regulation using an emulated inertia of the PMSG VSWT and with applying a droop control loop. The addition of droop control to the emulated inertia response is suggested to efficaciously supplement the dynamics of the prevalent synchronous machines.

Extensive simulations using MATLAB/Simulink are performed under different wind speeds, with a frequency drop caused by the insertion of large loads. Comparative results were presented to confirm the efficacy and the robustness of the proposed controller. The proposed APC algorithm is implemented for each PMSG VSWT of a wind farm composed of 25 PMSG VSWTs. This paper is arranged as follows; in section 2 the proposed power controller for normal operation of VSWT is introduced. In section 3 the proposed Centralized Active Power Controller (CAPC) is presented for frequency contingency mode of the VSWT. In section 4 the verification of the proposed CAPC is presented for two wind speeds. Finally, in section 5 conclusions are presented.

2. Centralized Active Power Control (CAPC) during Normal Operation

Wind turbines are the wind power extractor [21]. The challenge in intelligent networks is to develop a realistic model for the wind turbine power extracting process. Several research papers have proposed models for wind turbines to be used in grid connection and standalone studies, such as papers [22]-[24]. In each of the developed models certain important factors were ignored, which resulted in inaccurate implementations. A more accurate model is developed in based on the approach in [25]. Based on the control strategy design steps presented in [26], the normal operation mode is divided into two stages; the partial load stage, and the full load stage. An adjustable controller is proposed with a dual objective of energy maximization using generator control and loading exertion minimization using pitch control. The two controllers are both functioning where one is predominant and the other is contributory depending upon the wind profile. During the partial load stage, the contributory control is the pitch angle control. A proportional feedback controller (P-controller) is used, which produces the pitch speed (u) control input to the pitch actuation system. The proportional gain (K_P^{θ}) is calculated based on a linear model [26]:

$$K_P^{1\theta} \leq \frac{\pi}{4 \cdot (T_d^{\theta})} \tag{1}$$

Where, T_d^{θ} : The delay time = 1.3 s.

In the full load stage, the pitch angle controller is the predominant that limits the harvested wind power to its nominated value. Therefore, this controller basically reduces the mechanical loading exertion. The deviation in the rotor speed drives a Proportional derivative controller (P-D-controller) producing the pitch speed (u) control input to the pitch actuation system. The controller model is [26]:

$$C_{PD}(s) = K_P^f + K_D^f \cdot s \tag{2}$$

Where, K_P^f = 1.14 (°/s) / (rad/s), K_D^f = 17.33 (°/s) / (rad/s^2).

The functional block diagram of the proposed adjustable active power controller during normal operation is presented in Fig.1.

3. Centralized Active Power Control (CAPC during Frequency Contingency

The proposed frequency contingency control algorithm depends on releasing part of the stockpiled kinetic energy in the revolving cluster of the wind power plant for supporting the fundamental frequency of the power system using the combined response of the droop control and the emulated inertia. The addition of droop control to the emulated inertia is suggested to supplement the characteristics of the traditional synchronous generators, and further improve the response by minimizing the post-disturbance frequency perversion. In the following subsections the principles of the emulated inertia and the droop control are presented. Thereafter the proposed control algorithm is introduced.

3.1. The emulated inertia

The emulated inertia response is used to imitate the inertial rebuttal of the traditional synchronous generators over a bounded time frame promptly after a frequency contingency [1], [11], [16]. In normal operation the rapport between the electrical torque and the aerodynamic torque is defined by the swing equation.

The power electronics converter on the generator side manages the electric torque using the base value obtained from the electric torque/ rotor speed curve of the wind turbine as described in section 3 of this paper. In case of a sudden frequency change in the network, the idea of the emulated inertia is the release of the kinetic energy (E_k) stockpiled in the revolving cluster of the wind power plant [11]. The inertia constant H represents the kinetic energy stockpiled in the revolving cluster of the wind power plant at the rated revolving speed [11]. H is defined as [11], [16]:

$$H = \frac{1}{2} J_t \frac{\Omega_0^2}{S} \quad (3)$$

Where:

Ω_0 : The rated or maximum revolving cluster speed (r.p.m)

S : The rated apparent power (VA)

The inertia constant H is calculated at the maximum or rated rotor speed. This speed occurs at the rated wind speed, where at this wind speed and above, the extracted power will be constant at the rated magnitude. However, wind speed is variable and can be below that rated speed; hence the extracted power is lower than the rated power. In [16], a new term for H was proposed called "effective inertia constant"$H_e(\Omega_r)$. It is dependent upon the revolving speed Ω_r and the extracted wind output power,P_w and it is calculated as:

$$H_e(\Omega_r) = \frac{1}{2} J_t \frac{\Omega_r^2}{P_w} \quad (4)$$

When considering the effective inertia constant, the added temporary torque is represented as a function of the rotor speed as follows:

$$T_{inertia} = 2H_e(\Omega_r)\frac{d\Omega_r}{dt} \quad (5)$$

The principle of emulated inertia involves temporary variation of the operating electrical torque reacting to the perversion in the network frequency by adding $T_{inertia}$ obtained from Eq. (5) to the calculated operating torque (T_e) as in [26]. This new torque T_{en} value is as follows:

$$T_{en} = T_e + T_{inertia} \quad (6)$$

Supplying the torque with the emulated inertial response causes the torque reference magnitude to increase temporarily, slowing down the rotor so as to extract the kinetic energy required for the inertial reaction.

3.2. The droop control

Droop control of the wind turbines is based on a proportional controller that performs a droop-like load sharing characteristics [21]. It reacts to the frequency perversions by supplementing or deducting active power as a ratio of the rated power of wind power plant. The required active power is also extracted from the kinetic energy stockpiled in the revolving cluster of the wind power plant. This frequency control method needs coordination with the surrounding conventional power plants [14]. This strategy has the advantage that conventional power plants observe the real value of the power imponderables from the beginning, and compensates for the needed active power after the short contribution from the wind power plant, which persists only for a few seconds [14]. In [18], the main problem of using droop control is that the droop proportional constant (K_{droop}) has to be tuned appropriately for different power system compositions.

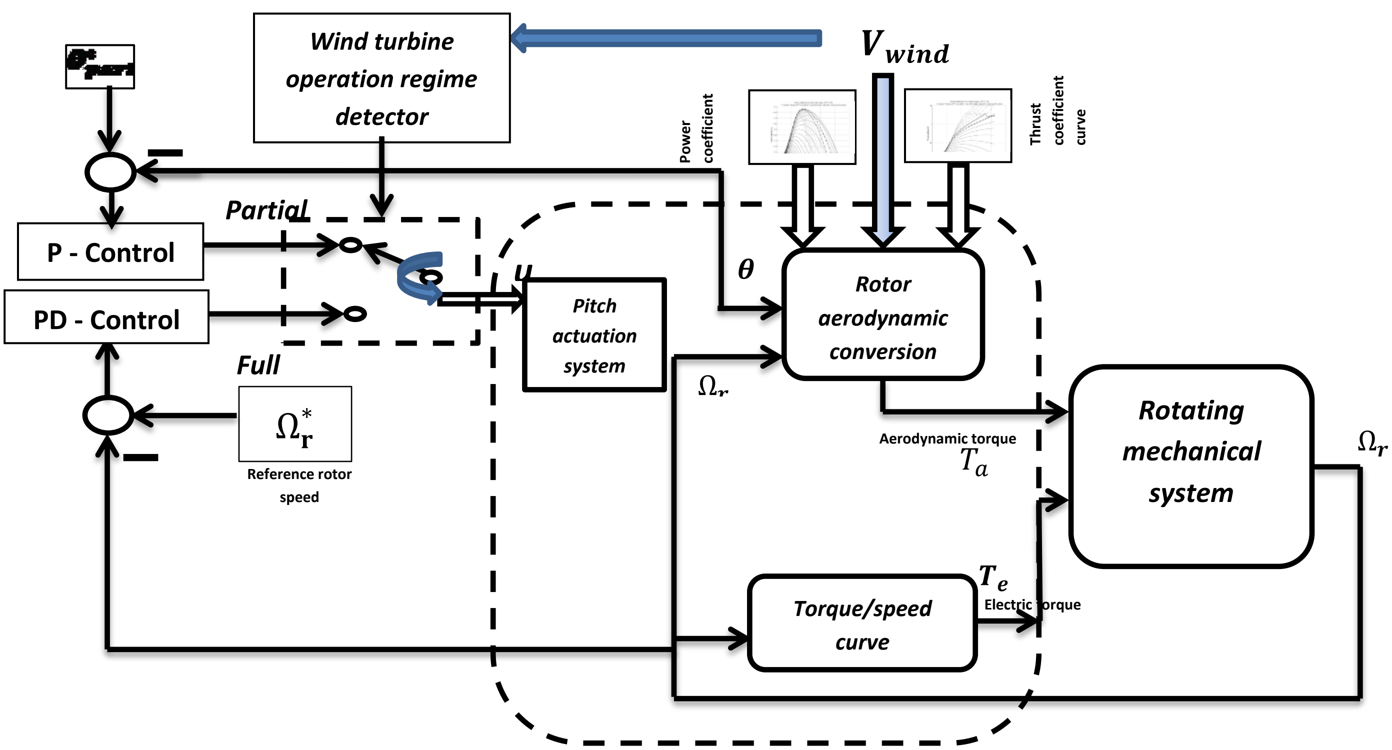

Fig.1 functional block diagram of the proposed adjustable CAPC during normal operation

The added temporary torque is extracted based on the absolute perversion of the rated revolving speed from the network frequency as [18]:

$$T_{droop} = K_{droop}(\Omega_0 - \Omega_r) \quad (7)$$

The new torque T_{en} value when adding droop control is:

$$T_{en} = T_e + K_{droop}(\Omega_0 - \Omega_r) \quad (8)$$

In [18], a higher value for the droop constant is preferred (1.05 – 2.1 MW/Hz). The droop control in wind turbine takes advantage of the ability of the VSWT power electronics converter to control its output power very fast.

3.3. The proposed Centralized Active Power Control (CAPC) during frequency contingency

The proposed frequency contingency control algorithm of a PMSG VSWT in this paper is based on imitating the inertial and primary frequency regulation performance of conventional power plants. In this case even completely decoupled PMSG VSWT type will increase the electric network inertia virtually. Each individual VSWT can contribute to the extra short term power required from the wind power plant by modifying the basic generator torque and blade. The added torque is based on two loops [27]:

1. The first loop is the emulated inertia loop which uses rotor speed derivative ($^{d\Omega_r}/_{dt}$) as an input (similar to the inertia response of the conventional synchronous generators);
2. The second loop is the droop control loop which uses rotor speed deviation ($\Delta\Omega_r$) from the reference value as an input (similar to droop control or governor response of conventional synchronous generators).

The complete new torque command in case of frequency contingency is based on the combination of Eq. (6) and Eq. (8) as follows:

$$T_{en} = T_e + T_{inertia} + T_{droop} \quad (9)$$

Fig. 2 shows the proposed Centralized Active Power Control (CAPC) during frequency contingency of a PMSG VSWT wind power plant, showing the operating torque resulting from the turbine torque/speed curve, and the added torque loops that get activated in case of a frequency contingency. The low pass filter (LPF) is used to reduce the disturbance produced after deriving the rotor speed to prevent harmful transient torques [17], while the high pass filter (HPF) is required to prohibit the participation of the droop control in steady state conditions [15],[18]. The proposed centralized active power control strategy is implemented to track the maximum power during normal operation and extract extra active power from the VSWT PMSG wind power plant during frequency disturbance.

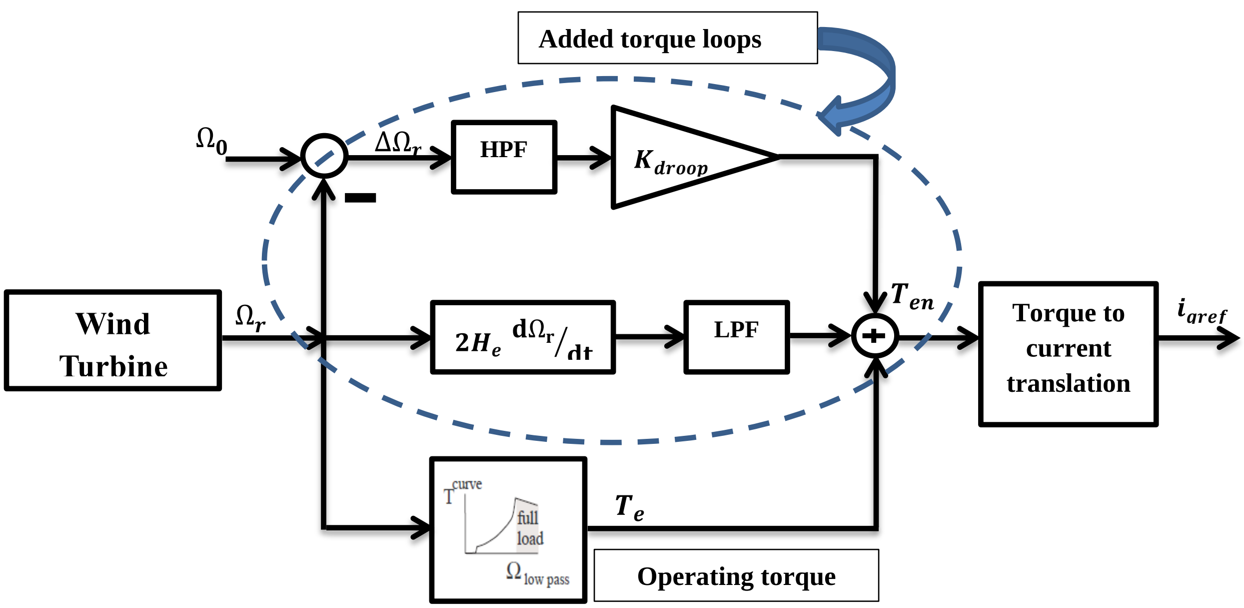

Fig.2 functional block diagram of the proposed CAPC during frequency contingency

4. Verification of the proposed CAPC for Normal and Frequency Contingency conditions

Dynamic frequency response testing of the wind farm composed of PMSG VSWTs equipped with the proposed frequency contingency controllers is carried out under different wind speeds. Fig.3 shows a one line diagram of the grid connected wind power plant or wind farm that is used for dynamic frequency response testing.

The network model represents a network of conventional power plants of 200 MVA rating. The nominal voltage of the system is 150 kV. The wind power plant is connected to the network through a 34 kV cable and a 34 kV/150 kV transformer. Two loads are used 100 MW, and 40 MW. The simulation time is 300 sec, the simulation starts with 100 MW load and at t =

150 sec the 40 MW load is inserted causing the network frequency to drop temporarily. In the test system, the wind power plant consists of 25 PMSG VSWT described in Table.1. The wind speed profile used for simulation is in two cases:

1- Normal wind speed (12.3 m/s)
2- High wind speed (19.68 m/s)

The base case for the simulations is the case with no wind farm, where the loads are supplied by the network with only conventional power plants. Four scenarios are used for the simulations at each wind speed, as follows:

1- The case with the wind power plant without frequency contingency controller or without the CAPC.
2- The case with the wind power plant with the CAPC using only the emulated inertia response.
3- The case with the wind power plant with the CAPC using only the droop control.
4- The case with the wind power plant with the CAPC using both the emulated inertia and droop control to imitate the performance of conventional power plants.

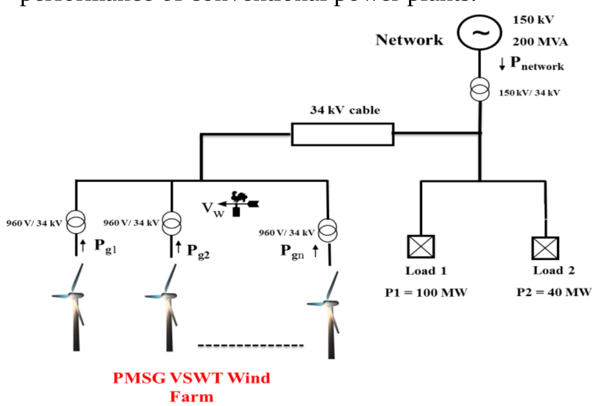

Fig.3 functional block diagram of the proposed CAPC during frequency contingency

4.1 Controller action at Normal wind speed (12.3 m/s)

The next simulation results are for the case with the normal wind speed scenario (12.3 m/s). The results are shown as per one PMSG VSWT as the response is assumed to be the identical for all other units of the wind power plant. Fig.4 shows the wind speed profile, Fig.5shows the generator torque, Fig.6 shows the electric power, Fig. 7 the pitch angle, Fig.8 shows the rotor speed, and Fig.9 shows the network frequency.

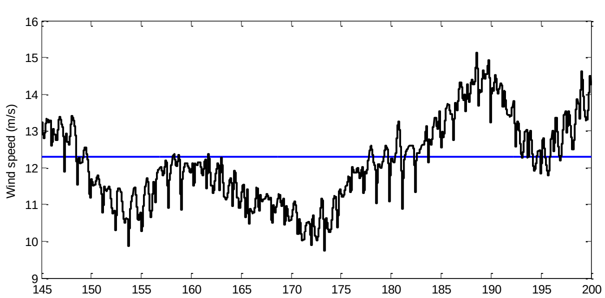

Fig. 4 wind speed profile (wind speed 12.3 m/s)

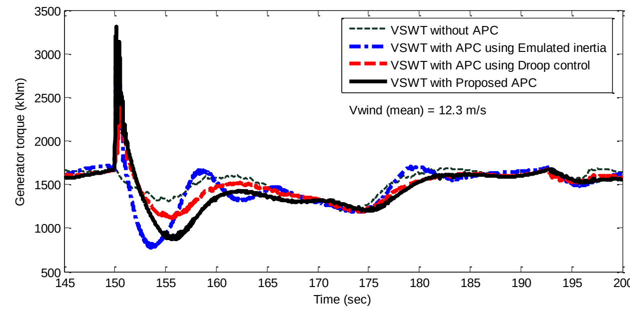

Fig. 5 generator torque per VSWT (wind speed 12.3 m/s)

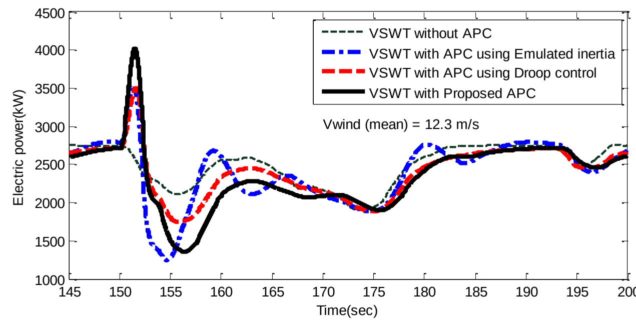

Fig. 6 electric power per VSWT (wind speed 12.3 m/s)

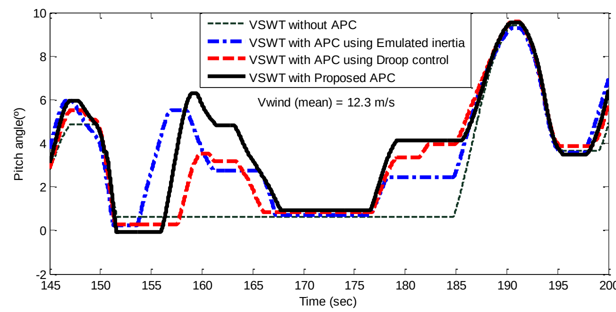

Fig. 7 pitch angle per VSWT (wind speed 12.3 m/s)

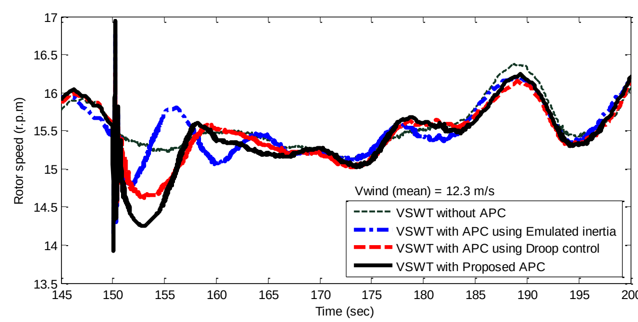

Fig. 8 rotor speed per VSWT (wind speed 12.3 m/s)

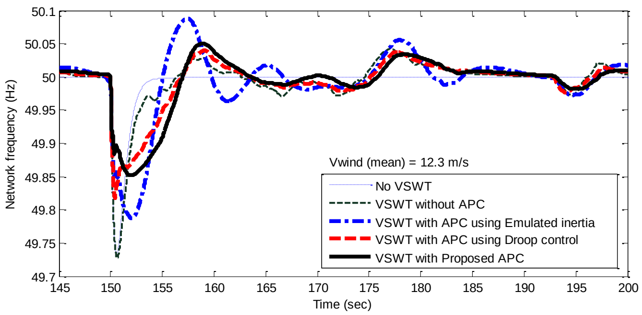

Fig. 9 network frequency (wind speed 12.3 m/s)

4.2 Controller action at high wind speed (19.68 m/s)

The next simulation results are for the case with the high wind speed scenario (19.68 m/s). The results are shown as per one PMSG VSWT as the response is assumed to be the identical for all other units of the wind power plant. Fig.10 shows the wind speed profile, Fig.11 shows the generator torque, Fig.12 shows the electric power, Fig.13 the pitch angle, Fig.14 shows the rotor speed and Fig.15 shows the frequency of the network.

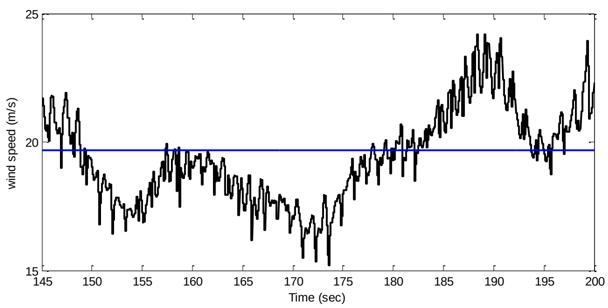

Fig. 10 wind speed profile (wind speed 19.68 m/s)

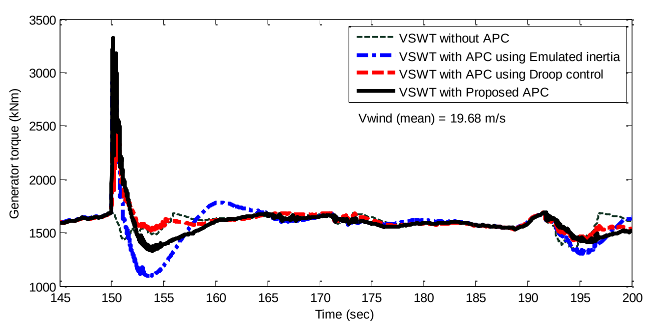

Fig. 11 generator torque per VSWT (wind speed 19.68 m/s)

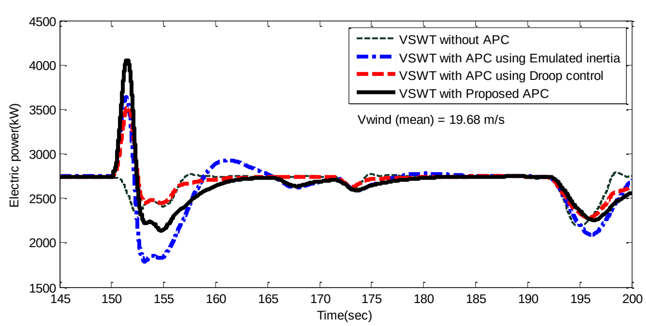

Fig. 12 electric power per VSWT (wind speed 19.68 m/s)

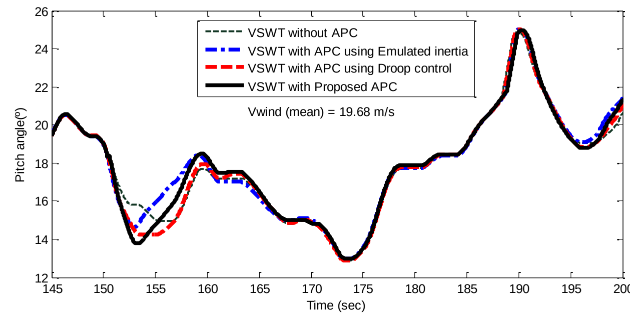

Fig. 13 pitch angle per VSWT (wind speed 19.68 m/s)

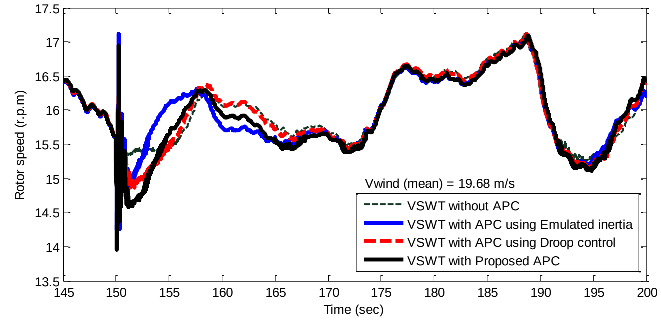

Fig. 14 rotor speed per VSWT (wind speed 19.68 m/s)

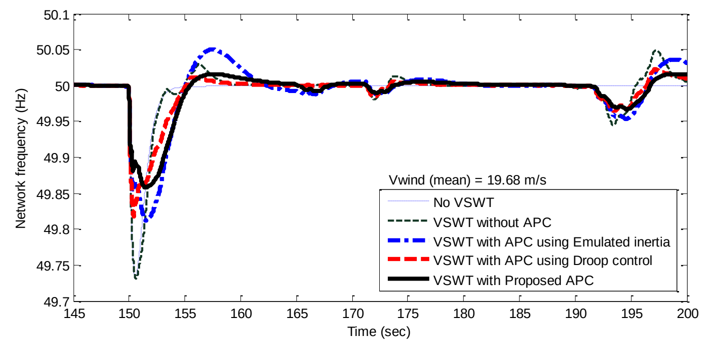

Fig. 15 network frequency (wind speed 19.68 m/s)

4.3 Discussion of the results

In response to the insertion of a large load, the frequency drops and the torque increases due to the temporary torque command based on the added torque control loops as seen in Fig.5 at the normal wind speed and Fig.11 at the high wind speed.

The decrease in the pitch angle admits more active power based on the stockpiled kinetic energy in case of the normal and the high wind speeds as noticed in Fig.7 and Fig.13. This action is mimicking the valves' opening of conventional steam turbines driving synchronous generators.

The extra power coming from the kinetic energy storage is higher for the proposed CAPC than for the emulated inertia and droop controllers for the two different wind speeds, as observed from Fig.6 and Fig.12. This implies that the contribution of the conventional power plants for the initial frequency response will be less for the proposed APC method. This extra power increases the GSC current; therefore there is a limitation that should be considered when using this method on the current rating of the converter.

Due to the insertion of a large load, the frequency dropped to 49.75 Hz. The frequency reaction is worse without CAPC due to the lower system inertia. The drop in frequency is significantly decreased using the proposed APC method at different wind speeds when compared to using either the emulated inertia or droop control alone. This can be seen in both Fig.29 at the rated wind speed and Fig.15 at the high wind speed.

In both Fig.9 and Fig.15 it can be noticed that the emulated inertia minimizes the frequency reduction and allows it to change tardily, because the overall system inertia has increased. However, it creates fluctuations in the frequency response. The droop controller of a wind turbine further improves the frequency response and reduces the post-disturbance steady state frequency aberration.

Using the proposed CAPC method with the value of effective inertia constant, and with the decrease in the revolving speed, the temporary torque decays. This decay has the merit of minimizing the net energy loss during the frequency disturbance period, thus removing the burden on the conventional power plants to compensate for this additional energy during the secondary frequency regulation stage.

From Fig.6 with normal wind speed of 12.3 m/s (rated speed) and Fig.12 with 160% of the rated speed (19.68 m/s), it is observed that at the time of the event the power increased to 4.05 MW with the proposed CAPC which means it increased only by 0.47 p.u (1300 kW pulse power is released for a discharge time of 2.5 seconds). From both Fig.8 and Fig.14, it is worth noting that the PMSG VSWT retrieved the normal rotor speed once the frequency disturbance is finished.

5. Conclusions

This paper proposed a Centralized Active Power Controller (CAPC) of a wind power plant during normal operation mode, and that can switch from that mode to the frequency contingency mode to support the network frequency based on the stockpiled kinetic energy of the revolving cluster. After responding to the frequency contingency, the controller retrieves the normal rotor speed. This maintains the stability of the network. For normal operation mode, this paper proposed an adjustable controller with a dual objective of energy maximization using generator control and loading exertion minimization using pitch control. For frequency contingency mode a transient active power control algorithm is proposed in order to imitate the response of a conventional synchronous generator. Simulations were performed under two different wind speeds, and proved the efficacy of the suggested controllers.

REFERENCES

[1] J. Aho, A. Buckspan, J. Laks, P. Fleming, Y. Jeong, F. Dunne, M. churchfield, L. Pao, K. Johnson, “A Tutorial of wind turbine control for supporting grid frequency through active power control”, Proceedings of the American control conference, Montreal, Canada, June 27-29, 2012.

[2] X. Yingcheng, T. Nengling, “Review of contribution to frequency control through variable speed wind turbine”, Renewable Energy, V. 36, p.167-1677, 2011.

[3] A. Causebrook, D.J. Atkinson, A. G. Jack, “Fault ride-through of large wind farms using series dynamic braking resistors”, IEEE Trans. Power Systems, 22(3), p. 966-975, March 2007.

[4] J.C.M. Vieira, W. Freitas, et.al., “Efficient Coordination of ROCOF and Frequency Relays for Distributed Generation Protection by Using the Application Region”, IEEE Trans On Power Delivery, 2006, Vol.21, No. 4, , p. 1878-1884.

[5] S. Taraft, D. Rekioua, D. Aouzellag, S. Bacha , “Proposed Strategy for Power Optimization of a Wind Energy Conversion System connected to the grid”, Energy Conversion and Management, Vol. 101, 2015, p. 489–502.

[6] N. Taib, B. Metidji, T. Rekioua, “Performance and efficiency control enhancement of wind power generation system based on DFIG using three-level sparse matrix converter”, Electrical Power and Energy Systems, Vol. 53, 2013, p. 287–296.

[7] A. E. Saleh , M. S. Moustafa, K. M. Abo-Al-Ez, A. A. Abdullah, “A hybrid Neuro-fuzzy power prediction system for wind energy generation”, Electrical Power and Energy Systems, V. 74, p. 384–395, 2016.

[8] I. Al-Bahadly, “*Wind turbines*”, InTech; 2011. p. 355–364 [chapter 15].

[9] D. Raoofsheibani, E. Abbasi, K. Pfeiffer, “Provision of primary control reserve by DFIG-based wind farms in compliance with ENTSO-E frequency grid codes”, IEEE PES Innovative Smart Grid Technologies, Europe, Istanbul, Turkey, Oct.12-15, 2014.

[10] J. Ekanayake, N. Jenkins, “Comparison of the response of doubly fed and fixed speed induction generator wind turbines to changes in network frequency”, IEEE Trans. Energy Conversion, 19(4), p.800-802, Dec. 2004.

[11] I.A. Erimnez, D.O. Bickers, G.F. Wood, W.W. Hung, “NGC experience with frequency control in England and wales – provision of frequency response by generators”, IEEE power engineering society winter meeting, p.590-596, New York, USA, Jan. 31 – Feb. 4, 1999.

[12] L. Holdsworth, J. B. Ekanayake, N. Jenkins, “Power system frequency response from fixed speed and doubly fed induction generator-based wind turbines”, Wind energy, Vol. 7, p.21-35, John Wiley & sons, 2004.

[13] G. C. Tarnowski, P. C. Kjaer, E. Sorenson, J. Ostergaard, “Variable speed wind turbines capability for temporary over-production”, IEEE power & energy society general meeting, Calgary, Canada, July 26-30, 2009.

[14] P. Keung, P. Li, H. Banakar, B. T. Ooi, “Kinetic energy of wind-turbine generators for system frequency support”, IEEE Trans. Power Systems, 24(1),p. 279 – 287, 2009.

[15] J. M. Mauricio,A. Marano,A. Gomez-Exposito,J. L. M. Ramos, “Frequency regulation contribution through variable-speed wind energy conversion systems”,IEEE Trans. Power Systems, 24(1), p. 173 – 180, 2009.

[16] L. Wu, D. G. Infield, “Towards an assessment of power system frequency support from wind plant – modeling aggregate inertial response”,IEEE Trans. Power Systems, 28(3), 2013.

[17] L. Zeni, A. J. Rudolph, J. M. Swendsen, I. Margaris, A. D. Hansen, P. Sorensen, “Virtual inertia for variable speed

wind turbines", Wind energy, Vol. 16, p.1225-1239, John Wiley & sons, 2013.
[18] J. Van de Vyver, J. D. M. De Kooning, B. Meersman, L. Vandevelde, T. L. Vandoorn, "Droop control as an alternative inertial response strategy for the synthetic inertia on wind turbines", IEEE Trans. Power Systems, 31(2),p. 1129-1138, 2016.
[19] B. Kirby, "Frequency regulation basics and trends", ORNL/TM-2004/291, Tech. Report, 2004.
[20] Y. Rebours, D. Kirschen, M. Trotignon, S. Rossignol, "A survey of frequency and voltage control ancillary services – Part I: Technical features",IEEE Trans. Power Systems, 22(1), p.350-357, 2007.
[21] M. Glinkowski, J. Hou, and G. Rackliffe, "Advances in Wind Energy Technologies in the Context of Smart Grid" Proceedings of the IEEE, Vol. 99, No. 6, June 2011.
[22] Y.J. Lin, "Simulating dynamic behavior of a grid-linked wind farm power system in Taiwan", Proceedings of the 12th IEEE Mediterranean Electro technical Conference, 2004.
[23] S. Santoso, H.T. Le, "Fundamental time-domain wind turbine for wind power studies", Journal of Renewable Energy, Vol.32, Issue 14, November 2007, p.2436-2452.
[24] C. Eisenhut, F. Krug, C. Schram, and B. Klockl, "Wind-Turbine Model for System Simulations Near Cut-In Wind Speed", IEEE Trans. On Energy Conversion, Vol.22, No.2, June 2007.
[25] S. Mathew, G. S. Philip, "Advances in Wind Energy Conversion Technology", Springer-Verlag Berlin Heidelberg, 2011.
[26] K. M. Abo-Al-Ez, R. Tzoneva, "Modelling and Adaptive Control of a Wind Turbine for Smart Grid Applications", International Conference of Commercial and Industrial Use of Energy (ICUE), Cape Town, South Africa, 2015.
[27] K. M. Abo-Al-Ez, R. Tzoneva, "Active Power Control (APC) of PMSG Wind Farm Using Emulated Inertia and Droop Control", International Conference on Industrial and Commercial Use of Energy (ICUE), 16-17 Aug. 2016, Cape Town, South Africa.