Voltage and Power Quality Improvement Strategy for a DFIG Wind Farm during Variable Wind Conditions

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***Abstract*—This paper presents a voltage and power quality enhancement scheme for a doubly-fed induction generator (DFIG) wind farm during variable wind conditions. The wind profiles were derived considering the measured data at a DFIG wind farm located in Northern Ireland (NI). The aggregated DFIG wind farm model was validated using measured data at a wind farm during variable generation. The voltage control strategy was developed considering the X/R ratio of the wind farm feeder which connects the wind farm and the grid. The performance of the proposed strategy was evaluated for different X/R ratios, and wind profiles with different characteristics. The impact of flicker propagation along the wind farm feeder and effectiveness of the proposed strategy is also evaluated with consumer loads connected to the wind farm feeder. It is shown that voltage variability and short-term flicker severity is significantly reduced following implementation of the novel strategy described.**

***Keywords*— DFIG, flicker mitigation, model validation, voltage variation, wind turbulence intensity, wind variability, X/R ratio.**

I. INTRODUCTION

Variability in wind generation has given rise to many issues in power distribution systems, such as voltage instability, power quality, and protection [1]. The power quality issues may vary based on the wind generator type, such that fixed-speed induction generators (FSIG) give rise to 3p/2p power oscillations due to the tower shadow effect [2-3] and power electronics based wind generators (e.g. doubly-fed induction generator (DFIG) and direct-drive synchronous generator (DDSG) wind generators) give rise to harmonics due to the power electronics switching. In addition, variable wind conditions cause voltage fluctuations, or flicker, irrespective of the type of wind generator [4-6].

In the published literature a number of voltage and reactive power control strategies are proposed for the DFIG wind farms. The DFIG based reactive power control strategies are mainly implemented for power factor control [7], voltage stability improvement (during grid faults) [8-9], and system loss reduction [10-11]. The control time scale of those strategies varies from milliseconds to hours based on the reactive power support required for the particular application. As an example, a power factor control scheme is implemented as a long term (hour or half-hour basis) strategy for the DFIG wind farms to comply with the grid code standards. During grid faults additional reactive power control strategies are implemented to support local voltage to improve the voltage stability of the local network and such strategies are typically limited to seconds. The reactive power control strategies for system loss reduction can be implemented based on an hourly or half-hour basis at wind farms. The main emphasis of this paper is on mitigation of flicker and reducing the voltage variability using an additional reactive power control scheme for the DFIG during variable wind conditions. The control time frame of the proposed strategy varies from seconds to minutes, and hence can be implemented as a medium-term reactive power control scheme for the DFIG.

The phenomenon of flickering of light sources has been become a significant important power quality issue for distribution networks due to large scale distributed generation applications especially during variable wind conditions. Typically, flicker is identified as a consequence of nonlinear loads connected to power distribution systems, such as arc furnaces, discharge-type light sources, and induction motors and defined as the human perception (visual sensation) of annoyance due to the fluctuation of luminous flux from a light source [12-13]. In the published literature, several studies can be identified on flicker measurement, analysis and mitigation for wind generation systems [4-6]. The study conducted by Larson analyzed the effect of flicker emission for a fixed-speed wind generator [4]. In [6] the authors have analyzed various factors affecting the flicker emission of wind farms such as mean wind speed, turbulence intensity, short-circuit capacity (SCC) and grid impedance angle (X/R ratio) using sensitivity analysis.

In addition, a number of studies has outlined flicker mitigation strategies for wind farms [5, 14]. In [5] the authors have proposed a control scheme for DFIGs, based on the grid impedance and power factor angle control using the grid-side converter (GSC) of the DFIG. In that scheme, the voltage fluctuation during variable speed operation was derived as a function of the grid impedance angle and the power factor angle. It is proposed to maintain the difference between the grid impedance and the power factor angle close to 90 degrees to mitigate the flicker emission from wind farm. However, this control strategy suffers from a deteriorated power factor and voltage stability issues at the point of grid connection, due to large changes in reactive power during variable wind conditions. In addition, certain authors have proposed flicker mitigation strategies using static-synchronous compensator (STATCOM) based solutions [14], however such solutions are unlikely to be financially viable for distributed generation

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applications. This study implemented a rotor-side converter (RSC) based reactive power control scheme for flicker reduction during variable wind conditions. The initial study [15], has illustrated the effectiveness of the proposed concept using constructed wind speed series for a 6 hour period, while in this study actual wind speed variation at a DFIG wind farm location has been used and short-term variations (i.e. 10 to 30 minutes voltage variation and short-term flicker severity) were analysed.

This paper is organized as follows. Wind farm data measurement and aggregated model validation for the DFIG wind farm is presented in Section II. Flicker theory and emission during variable wind conditions is presented in Section III. Section IV presents the voltage control scheme and its performance for the DFIG during variable wind conditions. Section V analyzes the performance of the proposed strategy under different system conditions. Finally conclusions and future work are presented in Section VI.

II. WIND DATA MEASUREMENT AND MODEL VALIDATION

A. Data Measurement

The Queen's University of Belfast (QUB) has installed GPS time-stamped phasor measurement units (PMUs) across the Northern Ireland (NI) power network. The locations of the PMUs are illustrated in Fig.1.

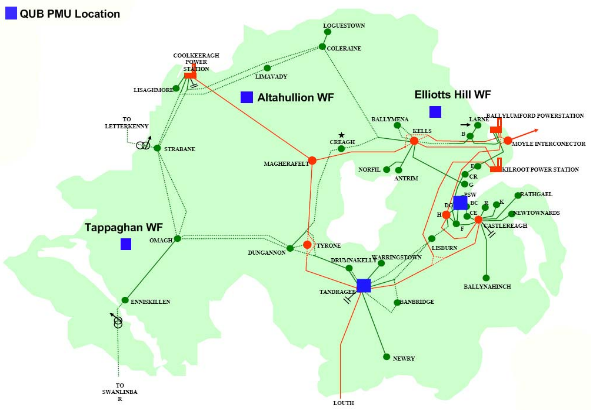


Fig. 1. QUB PMU network.

The wind farm related to this study is located in the south-west region of NI, and is based on the GE 1.5 MW DFIG wind generator, and total installed capacity equal to 19.5 MW (13 × 1.5 MW). A schematic diagram of the PMU based data acquisition system developed by the QUB is shown in Fig. 2.

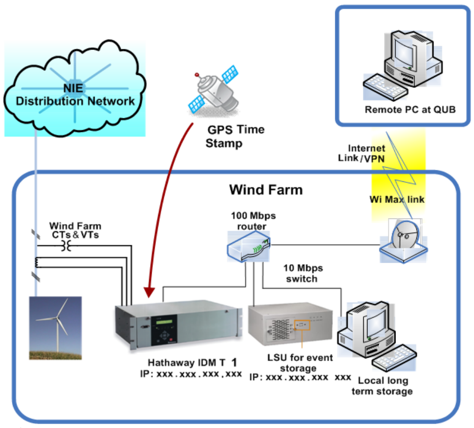


Fig. 2. QUB data measurement system.

The PMU is installed at the wind farm substation and data is typically recorded at 1 samples/cycle during continuous operation, while during fault conditions it is recorded at 128 samples/cycle for up to 1 s. The recorded data is stored at the local storage unit and can be accessed through the internet by the QUB workstation.

One of the objectives of this study is to develop and validate an aggregate wind farm model for the DFIG wind farm. The total power generation of the wind farm can be determined based on the captured data (phase voltage, current and power factor angle). The wind speed at the wind farm location is derived based on the following assumptions:

- All the wind generators in the wind farm are online
- Wind speed distribution is uniform over wind farm area

An approximated function was derived to extract the wind speed from the measured electrical power output of the wind farm based on the GE 1.5 MW power output vs. wind speed curve [16-17].

B. DFIG Model Validation

The DFIG is essentially a wound rotor induction generator (WRIG), with a rotor coupled voltage source converter, which is commonly known as the rotor-side converter (RSC). The RSC independently controls the active power and reactive power, and the control strategy is typically based on vector control techniques in the *dq*-reference frame. The grid-side converter (GSC) maintains the DC link voltage constant and operates at unity power factor. The rotor exports active power above synchronous speed, and absorbs active power below synchronous speed. Crowbar protection is used to protect the RSC from high current transients during transient disturbances. The schematic diagram of the DFIG model is illustrated in Fig. 3.

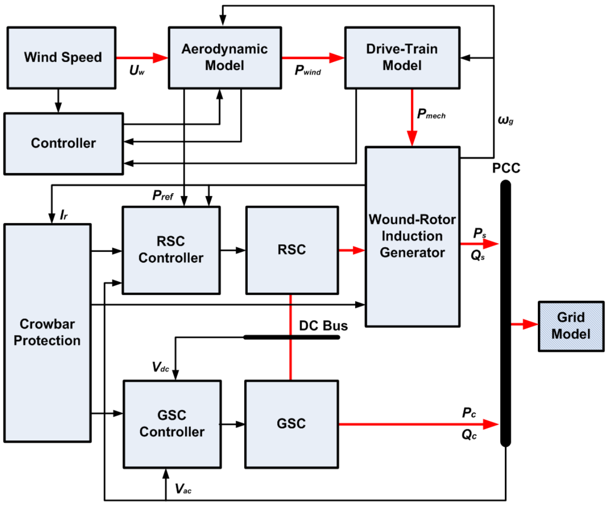


Fig. 3. DFIG simulation model.

The above model was first modified based on the turbine, drive-train, and induction generator parameters of the GE 1.5 MW wind generator. A test system was developed (see Fig. 4) in DIgSILENT considering an aggregated wind farm model for the wind farm which is connected to the transmission system by a 33 kV 10 km long distribution feeder (X/R =1). It is assumed that the voltage at the NI grid substation is stiff compared to the wind farm node. The wind farm was operated at unity power factor during the period of data acquisition and a 30 minute variable wind speed profile was used to validate the model. The control performance of the aggregate wind farm model was tuned by feeding the derived wind speed profile.

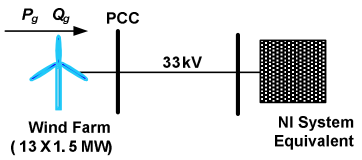


Fig. 4. Test system.

A comparison between measured and simulated active power variation for the aggregated wind farm model during a 30 minute period is illustrated in Fig. 5.

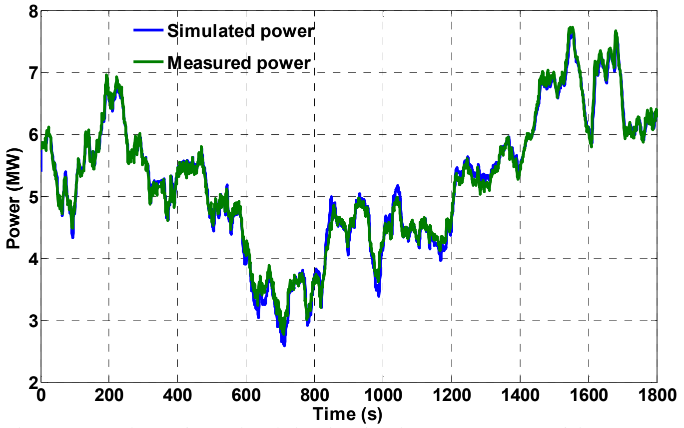


Fig 5. Comparison of actual and simulated active power output of the Tappaghan wind farm.

The active power output of the wind farm varies between 7.63 MW and 2.58 MW and indicates an accuracy of 98.6% between simulated and measured power output of the wind farm for the 30 minute period.

III. FLICKER THEORY AND VOLTAGE VARIABILITY DURING VARIABLE WIND

A. Flicker Theory

Voltage variations can be classified into several types, such as voltage dips, swells, collapse and fluctuations. The first three issues are directly associated with power system protection and stability. However, voltage fluctuations are identified as a power quality issue, which is defined in the range of ±10% of the nominal system voltage [12]. Flicker is identified as a type of voltage fluctuation with associated physiological and pathological components such as duress, and tiredness, due to the fluctuation of luminous flux during voltage fluctuations.

Flicker was initially measured considering the variations in the luminous flux of a light source. At present, the flicker measurement is conducted using electronic equipment, which characterize the light source and human perception using digital/analog filters. Fig. 6 illustrates a functional block diagram of a flicker meter.

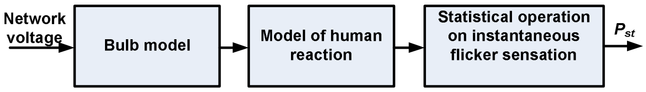
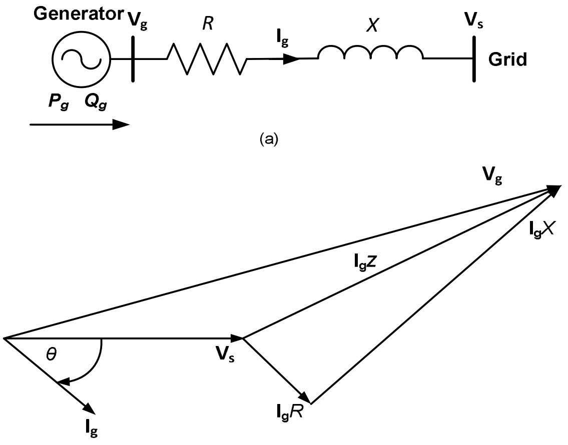


Fig. 6. Flicker measurement model.

The input to this instrument is the network voltage, which is fed into the bulb model to generate the typical characteristics of a light bulb for network voltage fluctuations. The output signal from the bulb model is then used to derive the human eye reaction based on a human eye and brain model. The human eye and brain model is developed as a band-pass filter. The output of this model is known as the instantaneous flicker severity, which is then used to derive the statistical measure of flicker severity known as short-term flicker severity (P_{st}) [12]. This is measured over a 10 minute period and calculated based on the cumulative probability function. In this study, a flicker meter has been implemented using MATLAB according to IEC 61000-4-15 standard [18] to measure the short-term flicker severity for the studied test system.

B. Voltage Variability during Variable Wind

Variable wind conditions cause fluctuations in power generation at wind farms, and ultimately cause voltage variations at the point of grid connection. This phenomenon can be understood by considering a generator feeding active and reactive power to an external grid via a distribution line (see Fig. 7).



(a)

(b)

Fig. 7. (a) Single machine system (b) Phasor diagram.

where P_g, Q_g, V_g, V_s, I_g, R, X, and θ represent active power generation, reactive power generation, generator end voltage, grid voltage, line current, line resistance, line reactance, and power factor at grid, respectively. From Fig. 4, the voltage difference between the generator and grid can be approximated as follows.

$$V_g - V_s = \Delta V = ZI_g = (R + \mathrm{j}X)(\frac{P_g - jQ_g}{V_g})\ ;\ Z = \sqrt{R^2 + X^2}$$

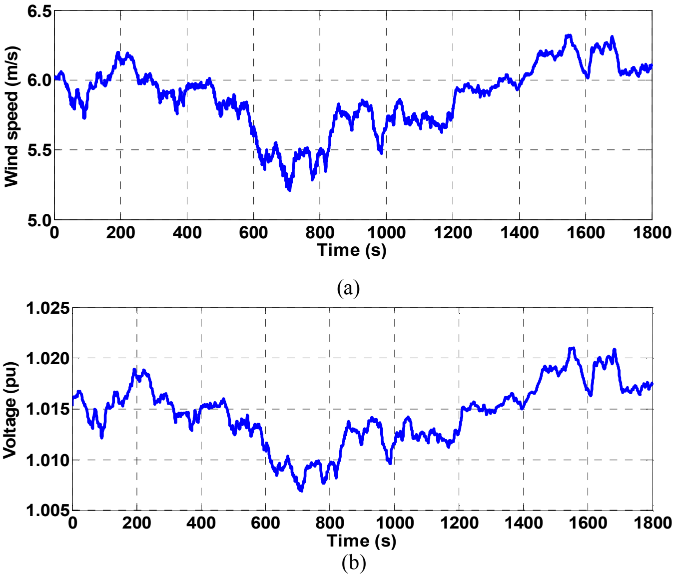
$$\Delta V = \frac{RP_g + XQ_g}{V_g} + \mathrm{j}\frac{XP_g - RQ_g}{V_g}$$

$$\Delta V = \Delta V_p + \mathrm{j}\Delta V_q \tag{1}$$

If it is assumed that the imaginary component in (1) is negligibly small compared to the real component, then the voltage difference simplifies to:

$$\Delta V \approx \frac{RP + XQ}{V_g} \tag{2}$$

According to (2), both the active and reactive power cause a voltage difference between the two ends of the distribution line. If the generator is a DFIG, the reactive power is typically maintained at zero (unity power factor) unless additional voltage or reactive power support is requested. Therefore, during variable wind conditions the DFIG reactive power can be considered as zero, and hence the active power is the only determinant of the voltage difference between the two ends of the distribution line. The voltage fluctuation at the wind farm point of common coupling (PCC) due to varying wind speed (with same wind profile as Fig. 5) is illustrated in Fig. 8.



(a)

(b)

Fig. 8. (a) Wind speed (b) Voltage at the PCC.

IV. DFIG CONTROL STRATEGY DEVELOPMENT

A. DFIG Control Strategy

Since the flicker control strategy is implemented at the rotor-side converter (RSC), the main focus here is placed on the RSC control scheme. The RSC control model basically consists of two control loops, i.e. a fast current control loop and a slow power control loop [9]. The fast control loop determines the phasor compensation and regulates the rotor current, as specified by the slow controller using the fast current control. The outputs of the fast controller are the respective modulation indexes for the *d*- and *q*-axis rotor voltage. The slow controller generates the current references for the fast controller, considering the active power and reactive power reference values. Typically, the active power reference is generated by the maximum power tracking (MPT) characteristic of the wind generator, while reactive power reference is kept at zero unless there is a reactive power or voltage control scheme implemented using the DFIG.

B. Proposed Strategy

The DFIG flicker mitigation strategy was developed based on the approximate relationship for the voltage difference in (2). According to (2), if the voltage difference is zero (ΔV=0), then the equation (2) simplifies to:

$$P = -\left(\frac{X}{R}\right)Q$$

Conversely, if a ΔP power variation causes a voltage difference, ΔQ reactive power response could mitigate the impact according to the following relation.

$$\Delta Q = -\left(\frac{R}{X}\right)\Delta P \tag{3}$$

According to (3), the reactive power response is based on the R/X ratio. However, due to the internal gains of a DFIG, and approximations made during the derivation of (2)-(3) this ratio may differ from the theoretical value. In general, the required reactive power compensation can be expressed as:

$$\Delta Q = K_{RX}\Delta P \tag{4}$$

The flicker control scheme was implemented as part of the slow controller of the RSC. The variation in active power is determined based on the moving average of the active power calculated over a time period. Then the deviation is integrated to derive the cumulative active power difference for a particular time frame before multiplication by the flicker control gain (K_{RX}). The functional block diagram of the RSC reactive power control scheme and flicker control scheme are illustrated in Fig. 9.

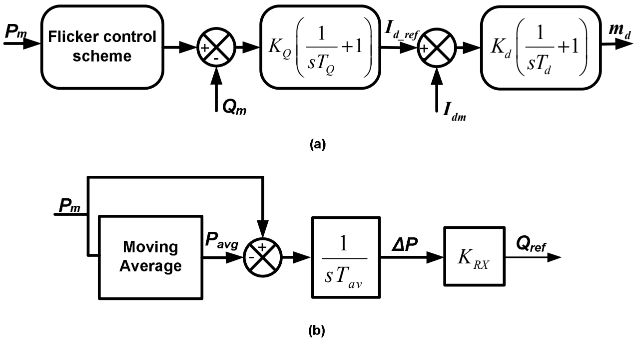
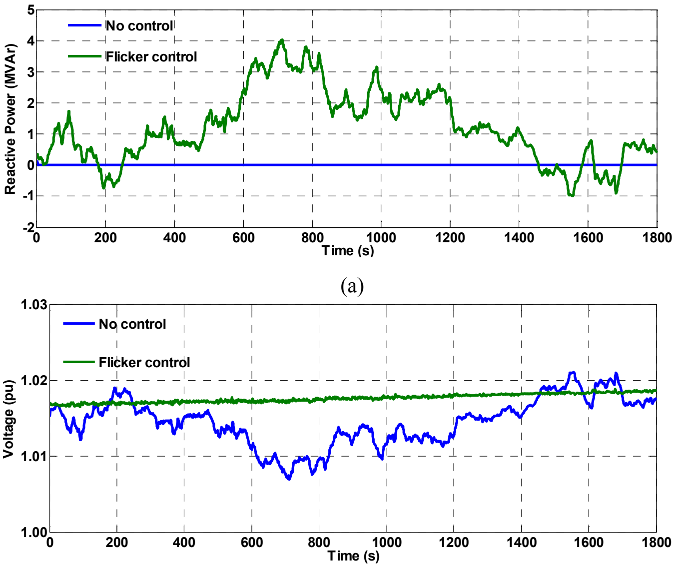


Fig. 9. (a) Reactive power control scheme of RSC (b) Flicker control scheme.

where P_m, P_{avg} Q_{ref}, Q_m, I_{d_ref}, I_{dm}, m_d, K_Q, K_d, T_Q, T_d, T_{av} and ΔP denote measured active power, moving average of the active power, reactive power reference, measured reactive power, d-axis current reference, d-axis modulation index, d-axis current reactive power control gain, d-axis current control gain, reactive power time constant, d-axis current time constant, integrator time constant and net active power difference respectively.

The time constants for reactive power (T_Q) controller and d-axis current (T_d) controller are 10 ms to 100 ms respectively, and the integrator time constant (T_{av}) is set as 500 ms. The value of K_{RX} mainly depends on the actual X/R ratio of the wind farm feeder. However, this value may change based on the integrator time constant and time frame of the moving average calculation. Further, the value of K_{RX} may slightly change based on the wind profile, since the active power deviation is influenced by the wind speed. This is because the DFIG follows different power vs. speed [19] characteristics based on the wind speed at a particular instance. The control performance of the proposed strategy is illustrated in Fig. 10.



(a)

(b)

Fig. 10. Performance of the control strategy (a) Reactive power (b) Voltage.

The voltage fluctuates between 1.02 pu to 1.007 pu before implementing the strategy, which is a 1.42% variation compared to nominal system voltage. The voltage variation has reduced to 0.23% following the implementation the strategy. Flicker severity also significantly reduced below the stipulated flicker standards for power distribution systems [20-21] (see Table I).

TABLE I
SHORT-TERM FLICKER SEVERITY

Time (minutes)	No Control	Flicker Control
0-10	1.12	0.012
10-20	1.12	0.015
20-30	1.16	0.014

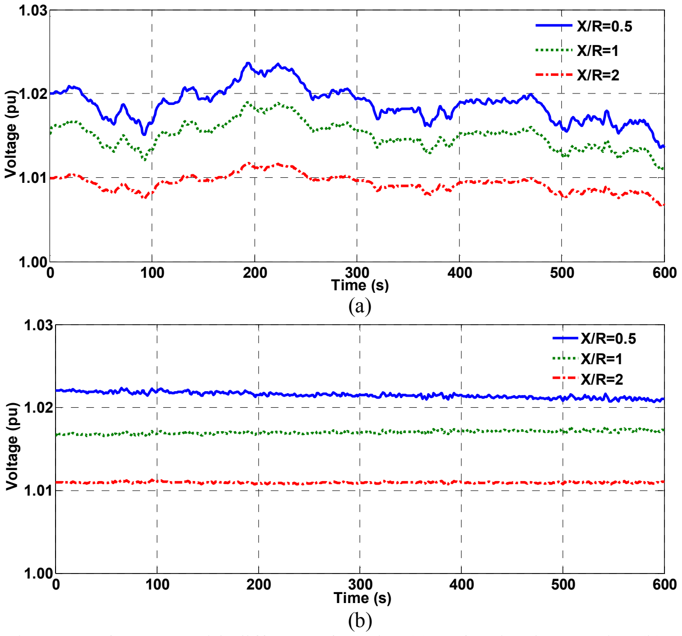
As an example, the standard in reference [19] requires short-term flicker severity less than 0.35 for power distribution systems and short-term flicker severity has been reduced below that standard after implementing the strategy. On average, the proposed strategy maintains unity power factor during the 30 minute period, however instantaneous power factor drops to 0.49 leading during periods with low active power generation (since reactive power generation increases to maintain bus voltage constant).

V. PERFORMANCE OF PROPOSED STRATEGY

The performance of the proposed strategy was evaluated considering a 10 minute wind profile measured at the NI wind farm. The control performance was evaluated with different X/R ratios, wind profiles and with consumer loads connected to the distribution system feeder.

A. Different X/R Ratios

The performance of the flicker mitigation strategy was evaluated with different X/R ratios for the distribution feeder which connects the wind farm and the grid. The variations of voltage at the PCC with different X/R ratios are illustrated in Fig. 11.



(a)

(b)

Fig. 11. Performance with different X/R ratios (a) Before implementation (b) After implementation.

The voltage variation has significantly reduced with different X/R ratios after implementation the proposed strategy. As an example, with X/R = 0.5 (see Fig. 11-(a)) it indicates a voltage variation of 1% compared to nominal system voltage and that has reduced to 0.16% after implementing the proposed strategy as observed in Fig. 11-(b). In terms of X/R = 2, it initially indicates a 0.5% voltage variability during the 10 minute period and that has reduced to 0.06% after implementing the strategy. The calculated short-term flicker severities for different X/R ratios are illustrated in Table II.

TABLE II
SHORT-TERM FLICKER SEVERITY WITH DIFFERENT X/R RATIOS

X/R ratio	No Control	Flicker Control
0.5	1.28	0.015
1	1.12	0.012
2	1.15	0.012

As indicated in Table II, before implementing the strategy it has indicated short-term flicker severities beyond the stipulated standards for power distribution systems. At low X/R ratios flicker severity is much higher, since the voltage variability due to the resistive component is high under such circumstances. However, flicker severities have reduced significantly below the stipulated standards for power distribution systems [20-21].

B. Different Wind Profiles

The wind turbulence intensity is one of the crucial factors for flicker emission of wind farms. The wind turbulence intensity (I) is calculated as:

$$I = \frac{\sigma_u}{\bar{u}}$$

where, $\bar{u}$ and σ_u denote the mean wind speed and standard deviation, respectively. This is measured over a 10 min. time period. The mean wind speed and wind turbulence intensities for the four wind profiles are shown in Table III.

TABLE III
WIND PROFILE CHARACTERISTICS

Wind Profile	Mean wind speed (m/s)	Wind turbulence intensity
1	6.88	0.033
2	7.65	0.046
3	5.20	0.073
4	10.79	0.002

The flicker severity was evaluated with and without the proposed strategy for each wind profile and illustrated in Table IV. High wind turbulence intensity has resulted in a large short-term flicker severity. As an example, a wind profile with the highest turbulence intensity (wind profile 3) has resulted in the highest short-term flicker severity (1.28), while the wind profile with the least turbulence intensity (wind profile 4) has the lowest short-term flicker severity (0.42). The wind turbulence intensity has also resulted in same influence on the proposed strategy (see Table IV).

TABLE IV
SHORT-TERM FLICKER SEVERITY WITH DIFFERENT WIND PROFILES

Wind Profile	No control	Flicker Control
1	1.12	0.012
2	1.17	0.012
3	1.29	0.015
4	0.42	0.009

C. Consumer Loads Connected to the Feeder

This section evaluates the impact on consumer loads connected to the wind farm feeder before and after implementation of the proposed strategy. The consumer loads are sited at equal distance to each other in the 10 km long feeder (see Fig. 12) and it is assumed that active power consumption of the loads are constant during the 10 minute period.

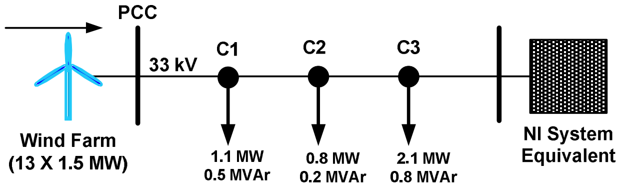
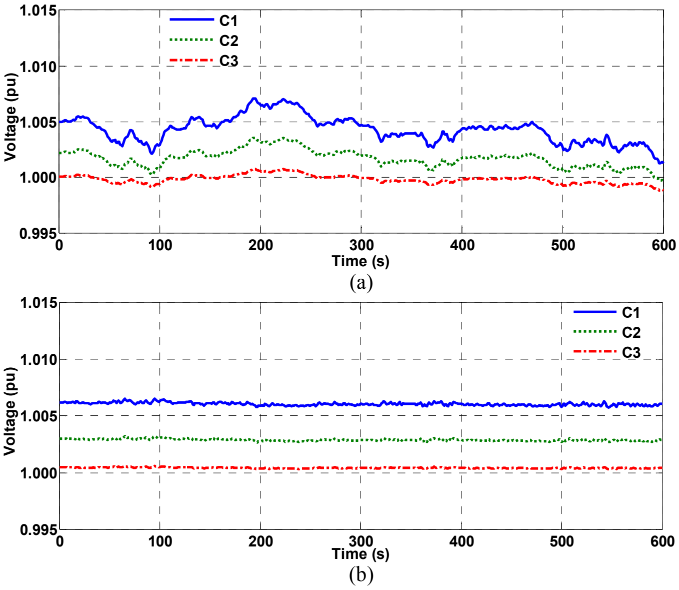


Fig. 12. Consumer load configuration of the distribution system feeder.

The variation of voltage at each consumer access point is illustrated in Fig. 13.



(a)

(b)

Fig. 13. Flicker severity at different consumer load centers (a) Before implementation (b) After implementation.

It can be seen from Fig. 13 that voltage variation get increased closer to wind farm and reduced when it closer to grid substation. As example, at consumer load *C1* indicates a voltage variation of 0.58%, and it has been reduced to 0.19% at consumer load *C3*. The corresponding values for those consumer loads were reduced to 0.08% and 0.03% after implementing the strategy. The variation of short-term flicker severity for each consumer load is shown in Table V.

TABLE V

SHORT-TERM FLICKER SEVERITY AT DIFFERENT CONSUMER LOADS

Consumer Load	No control	Flicker Control
C1	1.24	0.014
C2	1.21	0.014
C3	1.17	0.013

The short-term flicker severities are high closer to the wind farm location due to the variable wind farm output and have been reduced with the proposed strategy.

VI. CONCLUSIONS

A voltage and power quality improvement strategy for a DFIG wind farm based on X/R ratio of the wind farm feeder was presented in this study. The wind farm model was initially validated against the measured data at a NI wind farm. The proposed strategy has reduced the voltage variation and short-term flicker emission during variable wind conditions. The effectiveness of the proposed strategy was also testified with different X/R ratios, wind profile with different characteristics and with consumer loads connected to the feeder. It was shown that although they have an impact on voltage and short-term flicker variation, the proposed strategy can considerably reduce the voltage variation and the flicker emission during variable wind conditions. Future studies are expected to be carried out to evaluate the coordination of the proposed strategy with other reactive power control strategies implemented at different time scales.

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