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Comparative Power Quality Study of Variable Speed Wind Turbines

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Abstract – *Due to the variabilities inherent to natural wind resources and the associated electronic power present, wind power produces fluctuations in the generated power and harmonic injection entering the electric grid. This paper compares power quality issues and the impact on the power system of wind reliant power systems when using two different types of variable speed wind generators: the direct-drive permanent-magnet synchronous generator, and the doubly-fed induction generator. First, it gives an overview of the system structure of each generator, and then both systems are simulated to determine their behavior and the consequent impact on power quality. The power quality aspects addressed are voltage fluctuation (Flicker), current harmonics, response to voltage dip, and voltage stability. After this assessment, the contribution of both generators to severe three-phase faults was tested and then, finally, fault-ride through.* ***Copyright © 2009 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Wind power, PMSG, DFIG, Harmonics, Flicker, voltage Dip, short-circuit current, and fault-ride through.*

Abbreviations

PMSG	Permanent magnet synchronous generator
FDIG	Doubly-fed Induction Generators
WT	Wind Turbine
PCC	Point of common coupling
V, (m/s)	Wind speed, meter per second
S	Generator slip
In	Wind speed turbulence intensity
ΔV	Wind speed deviation
P_{st}	Short term flicker of individual wind Turbine
P	Wind turbine active power
Q	Wind turbine active power
R	Resistance of grid impedance
X	Reactance of grid impedance
V	Grid voltage
$P_{st.\ Total}$	Short-term flicker of total wind turbines
Ψ_k	Grid impedance phase angle
$C(\Psi_k, V_a)$	Flicker coefficient
S_k	Apparent power of short-circuit grid
S_n	Apparent power of rated wind turbine
T_p	Transient period for switching operations
U_n, U_{max}, U_{min}	Nominal, maximum and minimum R.M.S the value of the voltage at PCC
N_{WT}	Number of wind turbines
f	Nominal frequency
f_{DC}, f_{DC}	Harmonics frequency at DC and AC the converter's sides

I. Introduction

Today, renewable energies are seen as a desirable electrical energy source, because of their low impact on the environment and their abundance. Of these sources, wind energy has become one of the most utilized, and its usage is growing rapidly globally. At the end of 2015, the total installed wind power worldwide was around 392 GW, configuring nearly 4% of the world's electrical energy consumption [1]. Through the introduction of power electronic technology to wind turbine (WT), several advantages have been realized, such as captured power increments, a broader range of wind turbine operations at variable wind speeds and full control of both active and reactive power. By 2004, more than 60% of WTs applied variable speed topology [2]. Presently, the widest used generators in variable speed WT are permanent magnet synchronous generators (PMSG), and doubly fed induction generators (DFIG) [3].

The use of power electronics has however resulted in drawbacks, such as harmonics emissions [4]. Also, the natural variation in wind speed and the tower shadow effect introduces fluctuations in WT output power, causing voltage variations and possibly leading to flicker [5,6]. Furthermore, recently grid codes have been issued, requiring large WT generation units to remain connected to the grid during specified voltage drop caused by a fault, i.e. Fault-ride through [7].

Several guidelines have been issued in the last two decades to determine and investigate the characteristics of power quality variations caused by WTs integration. The first and most widely used guideline is the International Electrotechnical Commission, IEC 61400-21 [3].

There are many existing studies achieved to investigate and improve the power quality emitted by WTs over the years, voltage variations and flicker of two wind farms equipped with PMSG and DFIG were analyzed during continuous operation [8], both generators showed much lower flicker values than IEC standard limit. Refs. [9] and [10] presented factors that affect flicker of WTs, where the flicker found to be proportional to the mean wind speed, turbulence intensity and short-circuit power and grid impedance angle. In

Refs. [11] and [12], comprehensive studies were conducted for PMSG and DFIG to test the generator's capability to low voltage ride-through, it has been revealed, that PMSG has a better performance during fault than DFIG because it can provide much reactive power and it is fully decoupled from the grid.

Refs. [13] and [14] addressed the harmonics emission of DFIG, the current harmonics magnitude and their order variation with the generator slip as it related to the rotor frequency. The lower harmonic emissions occur when the slip is at or near zero. The harmonics of PMSG was reported in [15], where the total harmonic current distortion of PMSG was lower than the standard limit.

This paper provides a compressive power quality study and analysis for the two types of variable speed WTs, PMSG, and DFIG. The systems' performance was compared to assess the power quality drawbacks of both generators. The power quality was assessed according to IEC 61000-21. First, the paper includes a brief introduction of the generators, and then a simulation and comparison of the power quality issues were presented, i.e. voltage flicker, harmonics, active and reactive power control, response to voltage drop, short-circuit current and fault-ride through. The systems simulation was carried out using PSCAD/ETMDC, which is time-domain software and provides a powerful simulation tool well suited for transient electromagnetic study [16].

II. Permanent Magnet Synchronous Generator

The use of PMSG in wind power generation is growing because of its higher efficiency and no DC excitation needed. Also, PMSG construction allows mounting a large number of poles so it can be assembled with multi-pole which gives the choice of gearbox elimination [17]. However, PMSG with multi-pole is larger size and heavier, another drawback is the price of the permanent magnet materials, and the power electronics makes PMSG WT is expensive compared to other types [18]. Fig. 1 depicts the concept of WTs equipped with PMSG.

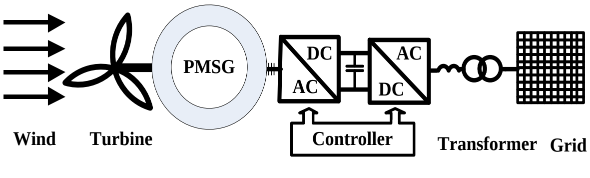

Fig. 1. PMSG Variable speed wind turbines structure [18]

As seen from Fig. 1; the PMSG is connected to the utility grid via full-scale power converter which allows a complete decoupling between the generator and the grid; the converter consists of two parts, the generator side which controls the generator; and the grid side which delivers the active and reactive power to the grid. A conventional vector control is adopted for both converter sides in this work, the control strategy and modeling are detailed in [19].

III. Doubly-Fed Induction Generator

DFIG is the most attractive generator among the other topologies because of its rigidity, lower converter price (in contrast to PMSG) and fully active and reactive power controllability [20]. The DFIG wind turbine is a wound rotor induction generator in which the stator winding is connected directly to the grid whereas a fully controlled converter is required to interface the rotor circuit to the grid [21]. The configuration of DFIG WT is shown Fig. 2.

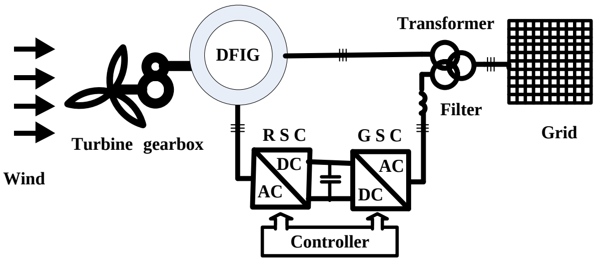

Fig. 2. DFIG Variable speed wind turbines structure [20]

Unlike direct-driven PMSG, a gearbox is necessarily needed to increase the DFIG rotor speed as the turbine rotor speed is very low. However, the presence of gearbox introduces disadvantages of more losses and regular maintenance demand. The DFIG converter divided into two parts, rotor-side converter (RSC) which controls the generator active and reactive power, and grid-side converter (GSC) which control the DC link and exchange the power with the grid. Typically, the power flows through the converter is limited to ±30% of the generator rated power [22]. The converter control chosen in this study is also a conventional vector control which is intensely discussed in [23].

IV. System Under Study

A case study of distribution network dispersed with WT is modeled and simulated to measure and assess the power quality produced by PMSG and DFIG variable speed WTs, and both topologies are equipped with back to back converter. The power system consists of a medium 11 kV distribution feeder with two generation units, the wind turbine, and infinite bus. There are five loads are connected to the feeder which are three similar linear loads with 0.8 lagging power factor, nonlinear DC motor load, and motorized load. Three transformers were installed to the feeder; two are employed to step-down the voltage at the main in-feed point and the motorized load connection point, the other is a step-up transformer to integrate the WTs. The wind turbine was operated under different speed, and all measurement and faults were conducted at PCC, a. The system parameters are provided in details in [24]. Fig. 3 illustrates a radial diagram of the proposed power system.

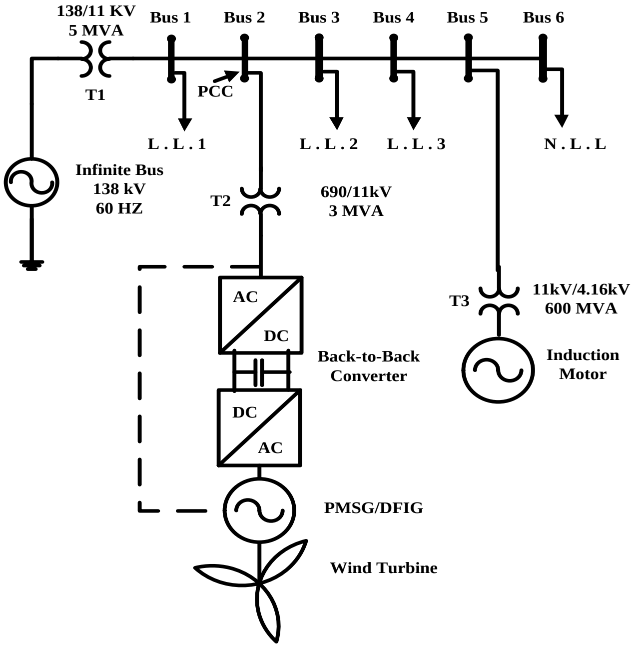

Fig. 3. Radial diagram of the case study [24]

V. Flicker Issue

The voltage variation in distribution line is calculated according to the equation (1) [25].

$$\Delta V = \frac{PR+QX}{V} \tag{1}$$

In the grid, integrated WTs, the wind variations, turbulence intensity ($In = \frac{\Delta V}{V}$), and tower shadow effect generate a fluctuation to the WTs output power which leads to voltage fluctuation and flicker at the PCC voltage which also depends on the grid characteristics (Ψ_k and short circuit capacity) [9]. According to IEC61400-21; the flicker level of WTs is quantified by P_{st} which are measured over the period of 10 minutes [26]. P_{st} measurement is achieved by a flicker meter developed by IEC61000-4-15[27]. The emission of P_{st} is limited by IEC6100-3-7 as given in Table I.

TABLE I
IEC 61000-3-7 FLICKER EMISSION LIMIT

	Planning level in MV	Planning level in HV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

IEC 61400-21 characterizes two situations for flicker measurement; continuous and switching operations. In the continuous operations; the standard requires WTs to state $C(\Psi_k, V)$ (which is the normalized measure of the flicker emission during continuous operation) for different values of wind speed and grid impedance angle [26]. $C(\Psi_k, V)$ is given by equation (2).

$$C(\Psi_K, V) = P_{ST} \frac{S_K}{S_N} \tag{2}$$

During switching operations, two aspects are taken into account; flicker step factor $k_f(\Psi_k)$ which is a standardized measurement of the flicker emission caused by a single wind turbine, and voltage change factor $k_u(\Psi_k)$ which is a normalized measure of the voltage change due to a switching operation of the WT [26]. $k_f(\Psi_k)$ and $k_u(\Psi_k)$ are given by formulas (2) and (3):

$$k_f(\Psi_k) = \frac{1}{130} \frac{S_k}{S_n} P_{st} \; T_p{}^{0.31} \tag{3}$$

$$k_u(\Psi_k) = \sqrt{3} \; \frac{U_{max} - U_{min}}{U_n} \; \frac{S_k}{S_n} \tag{4}$$

P_{st} emitted by PMSG and DFIG are tested in the case study described in section IV, and the results are illustrated in Fig. 4. where the wind speed started from rated to cut-in speed in step change of 1 m/s and ΔV = 20 %. The grid characteristics at the system PCC are $\Psi_k = 54°$ and short circuit capacity ($\frac{S_k}{S_n}$) = 31.

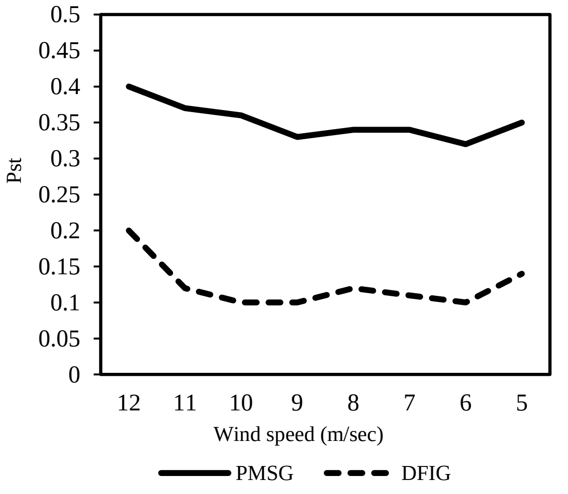

Fig.4. Short-term flicker for PMSG and DFIG

The simulation results in Fig 4 shows that both variable speed WTs have low flicker emission, and they are compliant to IEC6100-3-7 flicker emission limit provided in Table I. The mechanical stress (caused by tower shadow effect and wind characteristics) isolation gives the variable speed WTs the advantage of lower flicker in contrast to early stage (fixed speed) WTs [25]. Also, the full reactive power controllability reduces the voltage change by setting Q to zero which decrease the voltage change according to equation (1). In comparison to PMSG; it is noticeable from Fig. 4 that DFIG has lower flicker emission, this result from the fact that DFIG has two paths control; the output active and reactive power (rotor and grid side) which leads to smooth operation in output power and terminal voltage [28]. $C(\Psi_k, V)$ for the results from Fig.1 and PCC grid parameters are illustrated in Table II.

TABLE II
FLICKER COEFFICIENT OF PMSG AND DFIG

Wind speed (m/s)	Flicker coefficient PMSG	DFIG
12	4.0	2.0
11	3.7	1.2
10	3.6	1.0
9	3.3	1.0
8	3.4	1.5
7	3.3	1.4
6	3.2	1.0
5	3.5	1.8

In wind farm, the total P_{st} is proportional to the WTs numbers, and it may limit the WTs installation figure, equation (5) gives $P_{st.\,total}$ of wind farm [9].

$$P_{ST.\ total} = P_{ST}\sqrt{N_{WT}} \qquad (5)$$

For this reason, it is important to mitigate the WTs flicker even if the P_{st} of individual WT is lower, this is achieved by regulating the reactive power according to output active power, this method is detailed in [9], [25].

In switching operation, $k_f(\Psi_k)$ and $k_u(\Psi_k)$ should be stated at starting-up the WTs during cut-in, and rated speeds, Table (III) shows the results of $k_f(\Psi_k)$ and $k_u(\Psi_k)$.

TABLE III
FLICKER STEP FACTOR AND VOLTAGE CHANGE FACTOR

	Rated speed PMSG	Rated speed DFIG	Cut-in speed PMSG	Cut-in speed DFIG
Flicker step factor	0.031	0.086	0.02	0.06
Voltage change factor	1.558	2.07	0.51	0.52

From Table III, it is clearly appeared that PMSG has lower values of $k_f(\Psi_k)$ and $k_u(\Psi_k)$ compared to DFIG, this because the inrush current of DFIG stator causes a drop to PCC voltage, in addition, DFIG consumes a large reactive power to charge the stator which also contribute to voltage drop at PCC [11].

VI. Current Harmonics Issue

Based on IEC6100-21, WTs current harmonics (up to 50th order), interharmonics (up to 2 KHZ) and higher frequency components (between 2-7 KHZ) are required to be reported [26]. In this work; The measurement was accomplished at PCC with the aid of fast Fourier transformation (FFT) developed by PSCAD. As the IEC6140-21 does not apply any limitation to WTs harmonics emission, IEC61000-3-6 standard is chosen for this purpose, and it is provided in Table IV [29].

TABLE. IV
IEC61000-3-6 EMISSION LIMITS

Harmonic order	IEC 61000-3-6 current
3	-
5	5
7	7
9	-
11	3

The converter switching devices distort the current waveform and generate harmonics frequency in the DC and AC of 6 bridge which given in equation (6) [30], [31].

$$f_{DC} = \left|6k\right| f, \qquad f_{AC} = \left|6k \pm 1\right| f, \; k = 1,2,3, \ldots \qquad (6)$$

The results of current harmonics for PMSG and DFIG are demonstrated in Table V and VI consequently, the measurement were conducted under varying speed from cut-in till rated speed in step change of 1 m/s.

TABLE. V
CURRENT HARMONICS OF PMSG

Wind speed	Harmonics 3rd %	5th %	7th %	11th %	Total %
5	0.14	0.17	0.10	---	0.06
6	---	0.15	0.12	---	0.98
7	---	0.25	0.12	---	0.93
8	---	0.25	0.18	---	0.29
9	---	0.24	0.20	---	0.35
10	0.10	0.18	0.22	---	0.35
11	0.60	0.38	0.23	0.15	1.45
12	0.30	0.45	0.25	0.17	8.00

TABLE. VI
CURRENT HARMONICS OF DFIG

Wind speed	Slip %	Harmonics 3rd %	5th %	7th %	9th %	11th %	Total %
5	45	2.10	1.72	1.00	0.72	0.57	5.7
6	35	1.50	0.62	0.37	0.30	0.25	3.1
7	24	0.67	0.43	0.39	0.19	0.19	1.9
8	13	0.59	0.44	0.35	0.16	0.40	2.3
9	1.0	0.42	0.40	0.30	0.14	---	2.1
10	-8.0	0.57	0.45	0.56	0.22	0.15	3.3
11	-19	1.15	0.61	0.47	0.30	0.23	3.8
12	-30	2.30	2.00	1.25	0.75	0.75	14.5

The results show that the low-order harmonics 3rd, 5th, and 7th are the most dominated in current harmonics spectrum because of PWM switching and control system [32]. Tables V promise that PMSG is compliant to IEC61000-3-6 Emission limits. In DFIG case, the current harmonic depends on both, rotor and grid side converter, the rotor-side regulates the generator speed range operation by changing rotor voltage which is a function of slip [33], this make the magnitude of the stator harmonics is proportional to the slip value which is clearly approved in the results depicted in Table VI, the harmonics of DFIG is given by:

$$f_r = \left|6k(1-S)\pm 1\right|f,\ k = 1,2,3,\dots \tag{7}$$

VII. Voltage Dips Issues

The WTs response to voltage drops (caused by grid fault) shall be specified according to [26], the standard requires mainly three voltage drop conditions as following: 90%, 50% and 20% of the nominal voltage during 0.5, 0.5 and 0.2 seconds respectively. The fault shall be in two situations; 3 and 2 phase voltage drop. The WT's characteristics required to be stated during voltage dip are active and reactive power, active and reactive current and WT's voltage at terminals. In this paper, only 3 phase case (worse case) is considered. A three-phase short circuit applied to the case study at PCC to cause the voltage drop to roughly 90%. Fig. 5 and 6 illustrate the response of PMSG and DFIG.

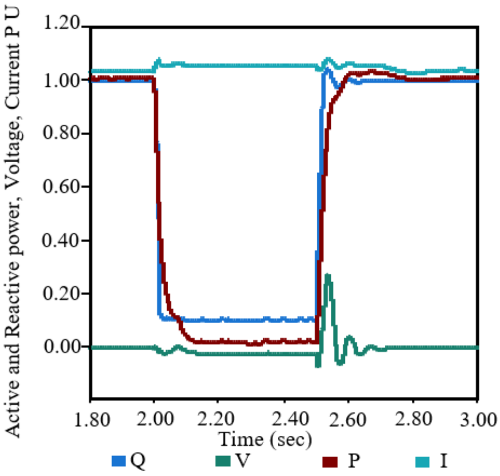

Fig. 5. PMSG WT terminals during voltage dip: grid voltage, active and reactive power and current

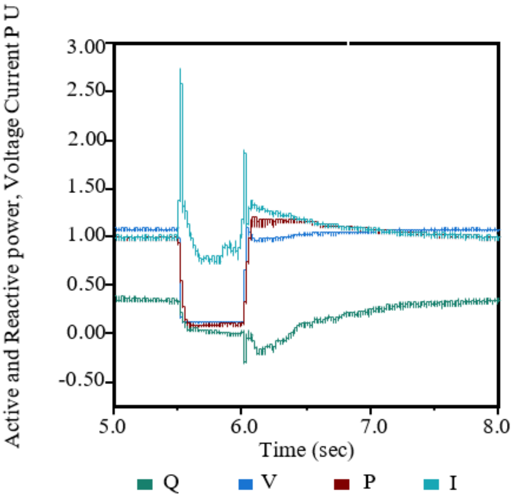

Fig. 6. Simulation results at DFIG WT terminals during voltage dip: grid voltage, active and reactive power and current

In Fig.5, when the fault applied to PMSG WT, the voltage dropped down to 10% of nominal voltage, this causes the active power to reduce too. However, WT's power still at its rated production, this power cannot be delivered to the grid as a result of sharp voltage reduction. Instead, the generator active power dissipates throw breaking resistor in the DC link. In the meantime, the reactive power kept at its reference value because P and Q are only transmitted from the grid-side converter which makes the Q and the current are feasible to be controlled [11], the current is usually set to 1.1 of its rated value; this can be proven from Fig.5 where the current was nearly within its ration. In the case of DFIG, the results are presented in Fig. 6, when the voltage drops; the stator voltage drops too due to direct connection of the stator, this leads to decreasing the flux in both the stator and rotor. Thus, the electromagnet torque falls causing active power to drops as well. Meanwhile, the stator demagnetises the magnet field stored in the stator causing the reactive power to arise. The high current at fault was occurring and clearing resulting from transient changing in the stator voltage and flux [11]. When the fault is clearing, the stator starts to recharge demanding large current as illustrated in Fig. 6.

VIII. Short Circuit Current Issue

In this section; the contribution of WTs to short-circuit current is evaluated. A sever symmetrical three-phase fault was applied at PCC when WTs were operating at rated power. Fig. 7 depicts the fault current at PCC with and without WTs.

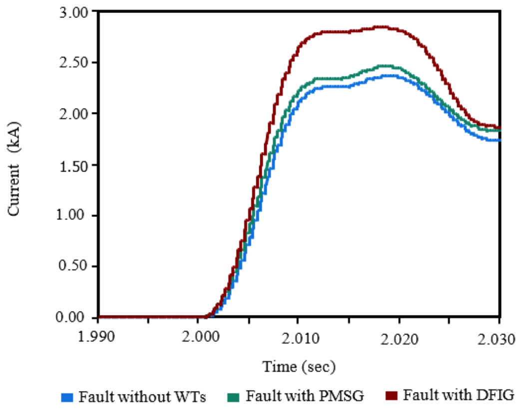

Fig. 7 short-circuit current at PCC

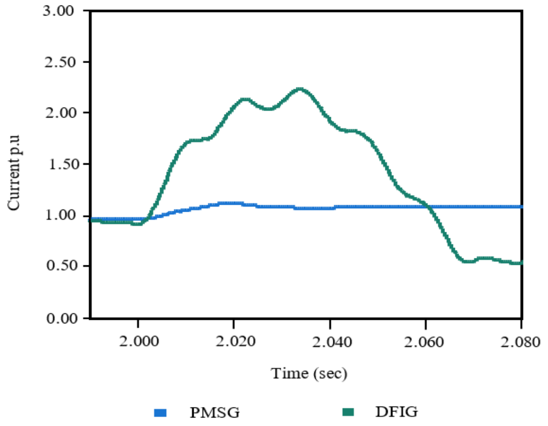

Fig. 8 PMSG and DFIG current during fault

Fig.7 reveals that DFIG has the higher fault current because of direct stator connection, the terminal voltage drops to or near zero when the fault occurs, this causes the flux space vector in the stator to stop rotating which result to DC component in the stator flux. On the other hand, the rotor flux still rotating (as it fixed to the rotor) and it generates alternating component to the stator flux [35], The resultant flux in the stator produces the voltage at WT terminals which cause fault current [36]. The oscillation of DFIG current in Fig.8 is caused by rotor flux. The magnitude of DFIG fault current depends mainly on leakage inductance of the stator and rotor whereas the stator and rotor transient time constants determine the time of fault current decay. Typically, DFIG is equipped with crowbar protection scheme to protect the converter from high current. The crowbar shortens the rotor winding during the fault by set resistors, by chosen appropriate value of these resistors, the fault current of DFIG can be minimized [35]. Compared to DFIG, PMSG shows a better performance during the fault which can be clearly seen in Fig. 7, this because, as mentioned in section VII, the GSC can control and limit PMSG current to its rated value which proven in Fig. 8.

IX. Active and Reactive Power Control

IX.1. Active Power Control

IEC 61000-21 requires to test WTs output active power; the maximum measured power shall be operated in continuous operation and at WT terminals as a 600 sec (P600), a 60 sec, (P60) and a 0.2 sec (P0.2) average values procedure. According to [6], P600 = P60 = P20 in variable speed WTs, so it was neglected in this work. The standard also requires to test the WTs ability to regulate the active power to a reference set-point starting from rated power down in steps of bin 0f 20% every 2 minutes until 20% of rated power, then increase it to 100%. Fig.9 presents the test results of PMSG and DFIG active power following the set-point active power as required.

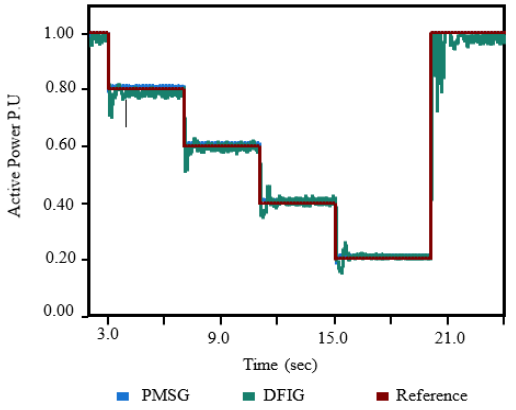

Fig.9. PMSG and DFIG active power

Fig. 9 guarantees that both WTs have fast respond of the active power to the change in their references and can precisely meet the standard requirement. PMSG shows slight faster performance compared to DFIG because the power can be controlled instantaneously by the inverter, in the case of DFIG; the power stored in the stator makes transient overshoot.

VII.2. Reactive power control

Similarly, to the active power, the reactive power should follow a set-point control specified by IEC 61000-21 which is the maximum of supplying and consuming reactive power during 50% of rated active power operation. Fig. 10 shows PMSG and DFIG reactive power according to the standard requirement.

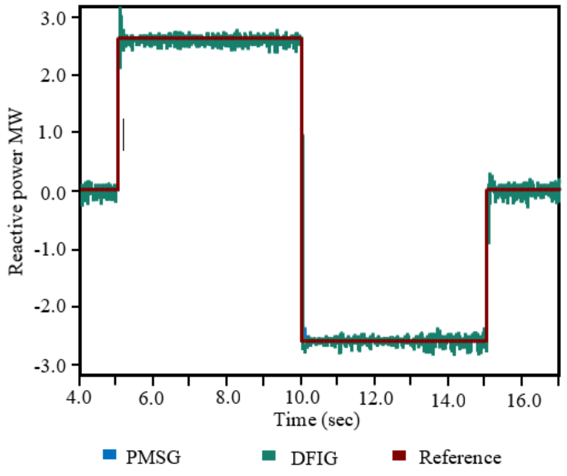

Fig.10. Measurement of reactive power set-point control for PMSG and DFIG

Based on Fig. 10, both WTs are capable of tracking the exact reactive power reference stated by IEC 61400-21 very rapidly. The WTs can switch from inductive to the capacitive mode in very short time (less than second), which give the variable speed WTs the advantage of subsidizing the voltage stability during the disturbance and can also contribute to flicker mitigation. PMSG has a slight fast response than DFIG because it produces the reactive power only from the inverter which acts like STATCOM [15]. In the case of the fault, PMSG can deliver full maximum reactive power whereas DFIG controller is blocked by the crowbar and it only can contribute to reactive power by the converter [11].

X. Fault-Ride Through

Different voltage profiles have been defined by the grid codes for which the voltage change over time, WTs are required to stay connected during the voltage sag. The voltage profile varies from grid code to another, but generally; the voltage falls to a very low value, then it recovers over specified time. The National grid voltage profile is adopted in this work where a fault occurs causing the voltage to drop to zero for 140 sec and then recover to 85% within 1.06 sec, after the fault clearing, the active power and voltage must be restored to 90% of the pre-fault situation [34], Fig. 11 and 12 depict the voltage and the active power at PCC for PMSG and DFIG respectively when voltage profile of the national grid is applied.

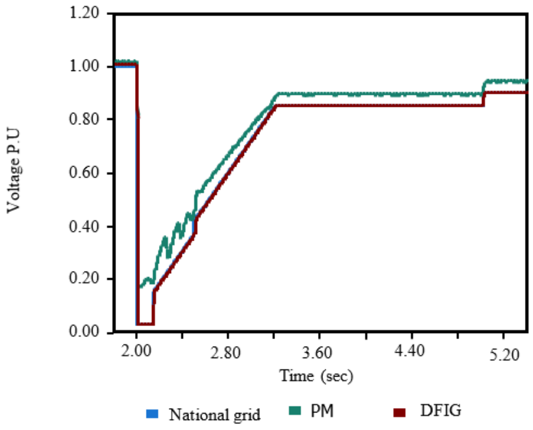

Figure.11: PMSG, DFIG, and National Grid fault-ride through voltage profile

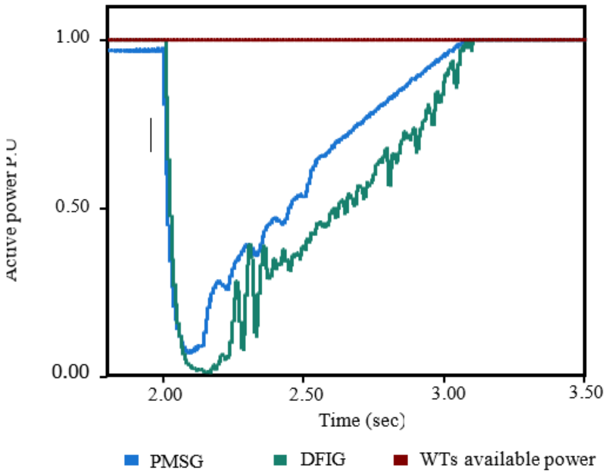

Figure.12: PMSG and DFIG active power

The results in Fig. 11 illustrated that PMSG has better behavior because of its ability to deliver reactive power even during the fault. In contrast, DFIF rotor circuit is shortened by RSC and then no longer the power control can be obtained. Thus, it conducts as induction motor which consumes reactive power instead. However, DFIG can only produce the reactive power of GSC during fault which has a rating of 30% of nominal power [11]. However, both generators are capable of remaining connected during voltage dip and can restore their active power when after voltage recovery as illustrated in Fig 12.

XI. Conclusion

This paper investigated two main variable speed WTs regarding power quality issues which are PMSG and DFIG. Both WTs have the nominal power of 3 MW and equipped with back-to-back converter. The addressed power quality problems are voltage flicker, current harmonics, response to voltage dip, short circuit current, active and reactive power control and fault-ride through. All results were presented (in tables or graphs) as comparable data to recognize the difference of both generators' impact on power quality and the power system. All measurements were performed at PCC and full power operation except the flicker and harmonics were measured under different wind speed according to IEC 61400-21 standard. The simulation results show several advantages of using PMSG concerning grid disturbances because of its fully decoupling converter and ability of supplying reactive power, during voltage dip and fault, PMSG preserves the current to rated value, but in DFIG; a large transient current occurs as result of stator-grid connection which may disturb the system stability, also regarding fault-ride through; PMSG has faster, smoother voltage recovery in comparison to DFIG because it can compensate the voltage drop by delivering reactive power during the fault where in DFIG case, the protection scheme deactivate the control and then no reactive power can be produced . On the other hand, DFIG has slightly less flicker emission. Both WTs shows faster respond to active and reactive power reference.

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