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A NOVEL ENERGY STORAGE SYSTEM USAGE BASED ON ULTRA-CAPACITOR IN VARIABLE SPEED WIND TURBINES (VSWT) FOR POWER IMPROVEMENT

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Abstract

Wind power as a renewable energy has the potential to become a clean energy source in almost all countries of the world but, there are lots of technical challenges that need to be addressed in advance. Wind speed variation (WSV) is one of the most important issues. Separate from its mechanical effects on wind turbines (WTs), it causes electrical power variations on WT as well. Doubly Fed Induction Generators (DFIGs) and Maximum Power Point Tracking (MPPT) system have been helpful so far but some problems such as inertia still needed to be solved. Inertia in the WTs causes a delay on MPPT.

This paper proposes a novel method to increase WTs output power in which a DFIG equipped with an energy storage system such as Ultra-capacitor helps MPPT system to track the wind variations rapidly by absorption or injection energy during the wind changes. The ultra-capacitor and control system are modeled and simulated in Matlab/Simulink® environment. The simulation results proofs that the proposed system can improve electrical power and increase electrical energy during WSVs. The simulation model will lead to more penetration of wind power and also enables engineers to optimize the system.

Index Terms - Doubly Fed Induction Generator (DFIG), Energy Storage, Power Improvement, Ultra-capacitor, Variable Speed Wind Turbines (VSWT).

Keywords: Energy, Storage, Capacitor, Wind Turbine

1. INTRODUCTION

A. *Previous strategies for increasing WTs electrical power.*

Knowledge of environmental pollution has caused huge desire to use clean energy [1] and Wind power has been considered as the main choice for production of clean electricity in many countries during the last decade [2]. Wind power has its effects when connected to a power system due to the nature of the wind and power electronic devices [3].Separate from the blade aerodynamic shape, a great deal of efforts has been done to increase wind power so far such as [4] which presents a solution to increase the efficiency of *WTs* with a *MPPT* system in *VSWTs*. The [5] suggests a short term prediction system and [6] suggests a network power injection into the *WT*. The [7] suggests usage of lighter moving parts in *WTs*. The [8] tries to put up the *WT* at the optimum power point of operation, by connecting a fly wheel to the *WT*.

The angular velocity (*AV*) of *WT* shaft is proportional to wind speed. However, due to the inertia of the *WT*,

the rotational speed of rotor is slightly behind its optimal value during *WSV* which causes captured power reduction. In a *WT* if we use an energy storage system to compensate mechanical system inertia, it can track *WSV* more precisely and as a result the output power will increase.

B. System description

This paper presents a novel system which increases electrical output power of a *VSWT* with ultra-capacitors equipped *DFIG* connected to grid during *WSV*s. After producing the system configuration modeling and simulation in the Simulink-Matlab®, the results are presented. It is demonstrated that ultra-capacitors can be used to increase electrical power.

The *VSWTs* with *DFIG* are becoming the most commercial and common type of wind energy source in the electricity markets of the world. Due to low power electronic converter rate and ability to supply power at constant voltage and frequency while the rotor speed varies [9], [10], [11], although the stand-alone operation of *DFIGs* is still feasible but the number of on-grid *DFIGs* are increasing in comparison with the other types of *WTs* [12]. One of the most important advantages of the *VSWT* as compared with conventional constant speed systems is the increase of wind power capture[7][9].

C. Lithium-ion Ultra-capacitor (LIUC)

Ultra-capacitors have been used in the wind power industry for many purposes so far. The [13] and [14] have presented a model and simulation of Ultra-capacitor. In [15] and [16] Ultra-capacitor has been used to improve power quality and harmonics elimination. In [17] it has been used for voltage sag compensation. In [18] and [19] ultra-capacitors are used for elimination of power oscillations and reduction of restrictions on active and reactive power in *WT* controllers. But here we suggest using ultra-capacitor to increase electrical power of *VSWT*s.

D. Objectives

In order to analyze the suggested Ultra-capacitor Energy Storage System (*UCESS*) associated with *VSWT* and DFIG, it is developed and the overall topology simulated in (Fig.1). In this system, the *WSV*s are detected by an observer and the appropriate control command is sent to different relevant parts. The ultra-capacitor, as an energy storage device, stores the surplus stator energy of the DFIG and injects it into the DC-Link when the rotor of WT needs to speed up because of the wind acceleration.

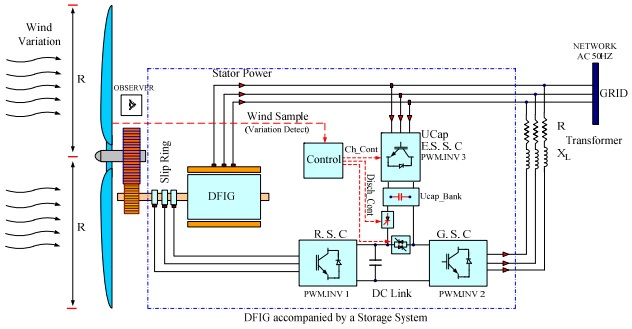

Fig. 1. VSWT WITH A DFIG ASSOCIATED WITH UCESS FOR VARIABLE SPEED WIND ENERGY STORAGE

2. MODELING

2.1 Model of the Turbine

The wind power which enters the WT can be calculated by (1) as [20]:

$$P_{Wind} = 0.5\rho.A.V_{Wind}^3 \tag{1}$$

Where ρ is the air density, A is the swept area of WT blade and V_{wind} is the wind speed.

The mechanical output power of a WT which is a nonlinear system is determined by (2) as [20]:

$$P_m = 0.5C_P(\lambda,\beta).\rho.A.V_{Wind}^3 \tag{2}$$

Where C_P is the *WT* power coefficient and represents the *WT* conversion efficiency. The value of C_P can be parametrically defined by (3) and (4) as [21]. The parameters values are given in (table1).

$$C_P(\lambda_i,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right).e^{\frac{-C_5}{\lambda_i}} + C_6\lambda_i \tag{3}$$

$$\frac{1}{\lambda_i} = \left(\frac{1}{(\lambda_i + 0.08\beta)} - \frac{0.035}{(\beta^3+1)}\right) \tag{4}$$

TABLE. 1. POWER COEFFICIENT (C_P) PARAMETERS

C_1=0.5176	C_2=116	C_3=0.4
C_4=5	C_5=21	C_6=0.0068

The C_P is the function of Tip Speed Ratio (*TSR* λ) and the Pitch angle (β) of the blade, in a pitch controlled *WT*. The *TSR* is the speed at the tip of the *WT* blades (*Rad/s*) to the speed of wind (*m/s*). It can be defined by (5) as [20]:

$$\lambda = \frac{\omega_r.R}{V_{wind}} \tag{5}$$

The *MPPT* system always tries to get the *TSR* optimum value (λ_{opt}) which can be obtained from equation (6). It calculates the λ_{opt} value that maximizes the power coefficient. Based on the wind speed, the corresponding optimal generator speed command for maximum wind power extraction is achieved by the optimum rotor angular speed ω_{r_opt}.

$$\lambda_{opt} = \frac{\omega_{r\_opt}.R}{V_{wind}} \tag{6}$$

Where: the ω_{r_opt} is the optimal angular speed of the *WT* rotor, *R* is the *WT* blade radius.

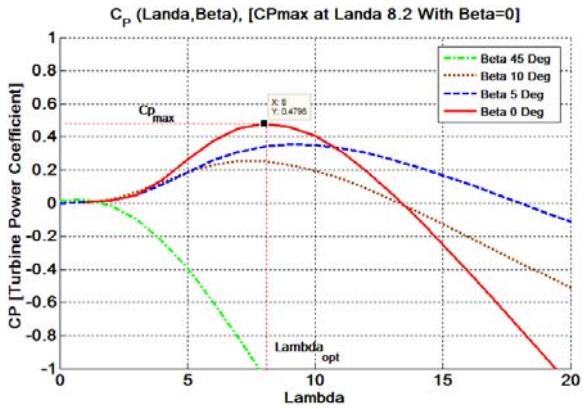

Fig. 2. AERODYNAMIC POWER COEFFICIENT *(C_P)* VARFIATION IN RELATION WITH λ

By (Fig.2), it becomes clear that C_{P_max} occurs at ω_{r_opt}. In fact with a *MPPT* system, the rotor of *VSWT* is controlled in such a way to obtain a pre-defined power-speed characteristic and get the optimum *AV* for every wind speed, which causes more energy extraction from the wind. But due to *WT* inertia, usually there is a delay between the *WSV*s and the rotor angular speed which causes output power reduction. By an energy storage system it becomes possible to eliminate the inertia and time delay. Since the *LIUC* has been used as an energy storage device, it is explained first.

2.2. LIUC Model

This paper uses a simplified equivalent *LIUC* Circuit model [13], [16]which is selected from three groups of models such as physical model [22],[23] Which is based on physical and electrochemical behavior of the Ultra-capacitors, the neural network model [24], and the equivalent circuit models [25],[26] built from series and parallel *RC* circuits whose combination results an accurate voltage current behavior on the terminals of an ultra-capacitor in the condition of charging or discharging. The terminal voltage of ultra-capacitors can vary between values 3.8V to 2.2V during charging/discharging process (table 2) [13]. The Ultra-capacitor model is shown in (Fig.3) which includes the most important parameters. The parameters values of this model are given in (table 3).It was observed that *LIUC* capacitance is nonlinear and dependent on the open circuit voltage which is approximated by the 4th order polynomial (7) with coefficients which are listed in the (table 4) [16]. Due to very low self-discharge, it is accepted to neglect it but in the simulation, it has been modeled by R_P. More experimental tests has been done in [13].The *LIUC* as an energy storage device has 10-20(Wh/Kg) energy density, while its power density is between 900-9000 (W/Kg) [13].

TABLE. 2. ELECTRICAL PROPERTIES OF THE LIUCS[13]

Property	Nominal	Limits
Voltage (V)	3	3.8
Current (A)	10-70	200
Low Voltage Cutoff (V)	2.4	2.2

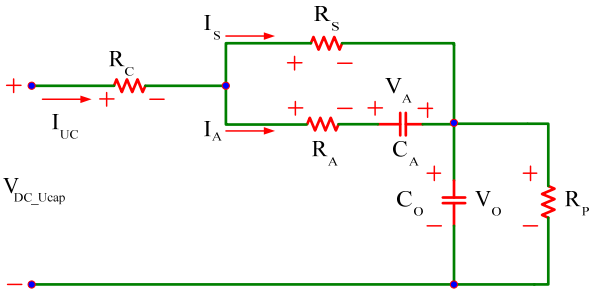

Fig. 3. LIUC EQUIVALENT CIRCUIT MODEL [13],[16]

TABLE. 3. LIUC MODEL PARAMETERS [16]

R_a[mΩ]	R_s[mΩ]	C_a[F]
[79.9]	[5.34]	[30.6F]

$$C_O = a.V_{OC}^4 + b.V_{OC}^3 + c.V_{OC}^2 + d.V_{OC}^1 + e \tag{7}$$

TABLE. 4. THE LIUC EQUATION COEFFICIENTS[16]

a	B	C	d	E
-703.394	9359.727	-45480.909	96048.083	-73516.729

The equations (8-14) can be achieved by applying *KCL* and *KVL* in *LIUC* equivalent circuit model as [16]:

$$KCL: I_{sc} = I_a + I_s \tag{8}$$

$$KVL_1: V_{dc\_Ucap} + R_c.I_{sc} + R_s.I_s + V_{co} = 0 \tag{9}$$

$$KVL_2: R_s.I_s - R_a.I_a - V_{ca} = 0 \tag{10}$$

$$I_a = C_a \frac{dV_{ca}}{dt} \tag{11}$$

$$I_{sc} = C_O \frac{dV_{Co}}{dt} \tag{12}$$

$$\begin{bmatrix} \frac{dV_{C_O}}{dt} \\ \frac{dV_{C_a}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C_a.(R_s+R_a)} \end{bmatrix} . \begin{bmatrix} V_{C_O} \\ V_{C_a} \end{bmatrix} + \begin{bmatrix} \frac{1}{C_O} \\ \frac{R_a}{C_a.(R_s+R_a)} \end{bmatrix} . [i_{sc}] \quad (13)$$

$$V_{DC\_Ucap} = \begin{bmatrix} 1 & \frac{R_s}{(R_s+R_a)} \end{bmatrix} . \begin{bmatrix} V_{C_O} \\ V_{C_a} \end{bmatrix} + \begin{bmatrix} R_c & \frac{R_s.R_a}{(R_s+R_a)} \end{bmatrix} . [i_{sc}] \quad (14)$$

The energy of the *LIUC* can vary between a maximum and minimum value and it is achieved by (15).

$$\Delta E_{Uc} = 0.5 C_{UC} (u^2_{Uc\_dcmax} - u^2_{Uc\_dcmin}) \quad (15)$$

Although the stored energy in an ultra-capacitor is more than a conventional capacitor, but it still inadequate for changing *AV* of a turbine with high inertia. By forming an ultra-capacitor bank (*UCB*), enough energy could be achieved. In order to inject the stored energy of the *UCB* into the rotor, it should be connected to Dc-link by its switches.

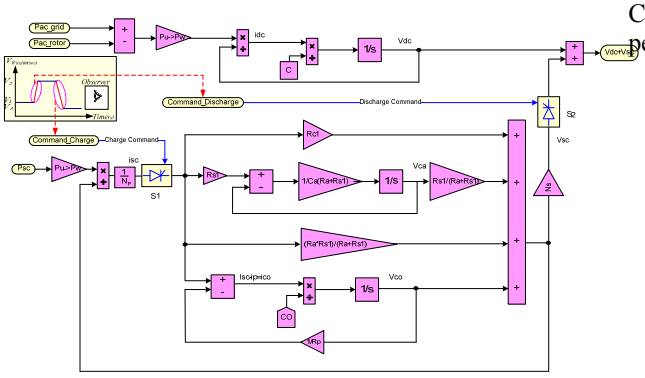

Fig. 4. THE PROPOSED LIUC BANK CONNECTED TO DC-LINK WITH SWITCHES S_1&S_2

Fig.4 illustrates the *LIUC* Bank model which is used in the simulation. N_S& N_P represent the numbers of cells (in series & parallel) and S_1&S_2 are the Charge/discharge switches.

It is clear that the *DC* voltage of the *LIUCB* would vary between a maximum and minimum during its operation but in order to have the best results; it needs to operate near its optimum value (*16*). The controller is programed to avoid falling below the minimum voltage.

$$U_{Uc\_opt} = \sqrt{0.5(u^2_{Uc\_dcmax} + u^2_{Uc\_dcmin})} \quad (16)$$

To produce the Dc-link 1,250 volts by the *LIUCB* in the worst case, *22* cells are needed in series so we have (17).

$$N_S = \frac{1250 - u_{DC-Link}}{u_{Uc\_min}} \quad (17)$$

This number of Ultra-capacitor cells will cause maximum 1281.4 volts in the Dc-link, therefor according to (16), the optimal value would be 1268 volts.

By injection of the ultra-capacitor bank energy into the *DFIG* rotor or storing surplus power of *DFIG*, acceleration or deceleration of a *WT* could be achieved.

2.3 The *UCES* System

During the *WSV* in a *VSWT* having *MPPT* system, the extractable power of the *WT* is controlled to achieve a pre-set power-speed characteristic. Because of *WT* inertia, usually there is a delay between the *WSV*s and the corresponding rotor angular speed which causes output power reduction. In order to increase the electrical output power of the *WT* during these changes, the *UCESS* is used. This system stores surplus energy by absorbing the stator excess energy during the decrease of wind speed (*Fig.6A*) causing deceleration of the *WT* rotor during the time period of (t_3-t_4) (*Fig.5*) and on the other hand it injects sufficient stored energy into the rotor when wind speed increases (*Fig.6B*) Causing acceleration of the *WT* rotor during the time period of (t_1-t_2) (*Fig.5*).

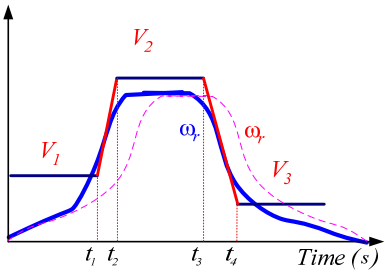

Fig. 5. SURPLUSE ELECTRICAL POWER STORAGE IN UCB DURING (t_3-t_4) AND INJECTION UCB POWER INTO DC-LINK DURING (t_1-t_2)

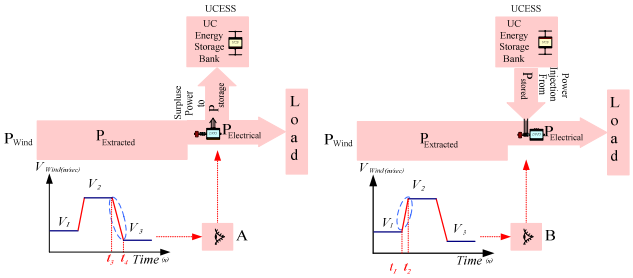

Figure. 6. UCESS CONTROLLER, STORAGE /INJECTION OF ENERGY

Both of these actions are applied to overcome the inertia of the *WT* and would let the *MPPT* system to follow its target faster than before. It causes an increase of *DFIG* electrical output power as a result. These two functions

significantly cause the C_P Correction as well. The output signal of controller is shown in (*Fig.11*).
UCESS charge/discharge simplified switching diagram is illustrated in (*Fig.7*). The Ultra-capacitor Convertor stores stator excess power ($P_{\_UC.conv}$) in the *UCB* during the period (t_3-t_4), while the switches (S_1, S_3) are closed and S_2 open. During the period (t_1, t_2) the switches S_2 are closed (S_1, S_3 open) causing power injection to Dc-link.

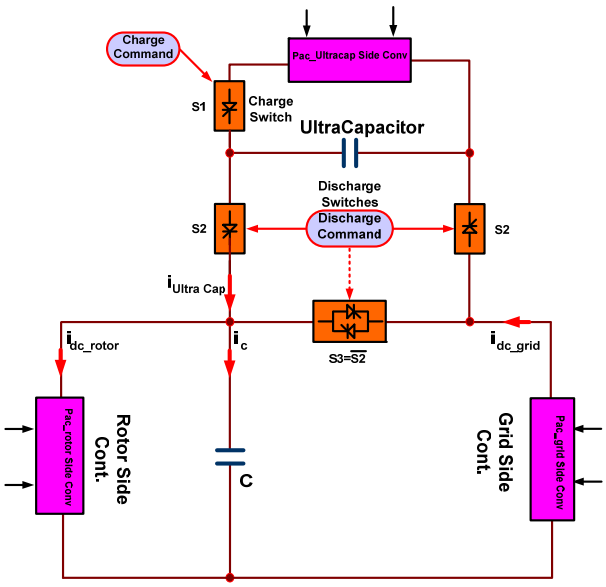

Fig. 7. THE PROPOSED LIUC DC-LINK CONNECTION WITH ITS SWITCHES

In order to have better performance of *UCESS*, the *UCB* should never be fully charged to *3.8V/Cell* or fully discharged to 2.2 *V/Cell* otherwise it would not act perfectly correct. To meet this limitation, the stored energy in the *UCB* and the energy storage of *UCESS* should obey the equation (18).

$$\Delta E_{UCB\_Stored} = 0.5C_{UCB}(u^2_{Ucb\_dcopt} - u^2_{Ucb\_dcmin}) = \Delta E_{UCB\_Storeable} = 0.5C_{UCB}(u^2_{Ucb\_dcmax} - u^2_{Ucb\_dcopt}) \quad (18)$$

Therefor the optimum voltage would be very close to the mean value of the voltage (19).

$$u_{Ucb\_mean} \approx u_{Ucb\_dcopt} = \sqrt{0.5(u^2_{Ucb\_dcmax} + u^2_{Ucb\_dcmin})} \quad (19)$$

2.4. The DFIG

As it is shown in (*Fig.10*) Associated with a *VSWT*, an on-grid *DFIG* phasor model has been used which is the same as the wound rotor asynchronous machine with the positive-sequence equipped with a Back to Back (*AC/DC/AC*) converter which has three main components: the Rotor-Side Converter (*RSC*), the Grid-Side Converter (*GSC*) and the Dc-link which connects these two converters. The converters are located between the rotor and the grid, have the ability to convert the electrical power to both sides. There is also a capacitor acting as a DC voltage source in the Dc-link. The three-phase stator windings are directly connected to the grid and the three-phase rotor windings are connected to *RSC* by slip rings and brushes.
The *UCESS* is added to the combination of *WT*& *DFIG*. This system has also an observer which receives the wind signal to analyze and detect the increase or decrease of wind speed. An additional convertor, as the Ultra-capacitor Convertor (*UCC)* is added and directly connected to the stator to use its surplus power to charge the *UCB* during wind signal falling time (*Fig.6A*).The system also helps the *WT* to speed up faster than before during wind signal raise by injection the stored energy of *UCB* into the Dc-link (*Fig.6B*). Although the *GSC* controls the Dc-link voltage level, but during the injection of *UCB* power into the Dc-link, the stored electrical power of Ultra-capacitors (P_{Ucap_stored}) effect on the Dc-link and causes DC voltage rise which could be calculated by (20).

$$V_{Dc-Link} + N_s\left[V_{C_O} + \frac{R_s}{(R_s+R_a)}.V_{C_a} + R_c.i_{sc} + \frac{R_s.R_a}{(R_s+R_a)}.i_{sc}\right] \quad (20)$$

Since the *RSC* has the ability to supply the suitable power which is needed by the rotor, the Dc-link voltage rise causes acceleration of the rotor angular speed and also a rise of *DFIG* electrical output power (*Fig.19*).
From the grid side point of view, to maintain the power balance, the stator, rotor and Ultra-capacitor power are algebraically added. In order to calculate the Dc-link power the equation (21) could be used, if the converter loss is neglected.

$$P_{dc} = P_{ac\_gs.Conv} + P_{ac\_rs.Conv} + P_{Uc.Conv} \quad (21)$$

The $P_{Uc.Conv}$ is the injected Power by *UCB* into the Dc-link only during the wind signal rise.

2.5. Lithium-Ion *UCES* System control

The function of *UCES* control system can be summarized and explained by the presented flowchart (*Fig.8*). The novel proposed algorithm of *UCESS* operation causes a power increase in *VSWT* with *DFIG*. In this method a central control observes the wind signals and modifies the electrical output power of the *DFIG* which is based on energy storage/injection of a

LIUCB. It is easy to implement the system since it is a simple method.

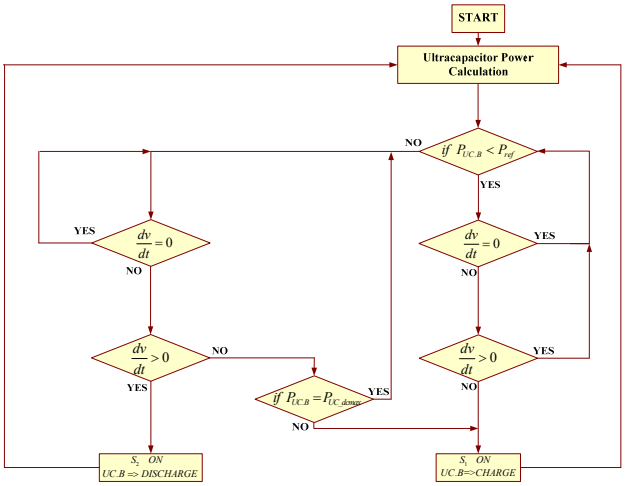

Fig. 8. LITHIUM-ION UCESS FLOWCHART (OBSERVATION & CONTROL) METHOD FOR POWER IMPROVEMENT

2.6 Turbine Model

As it is mentioned in (*1.4*) a *VSWT* Associated with a *DFIG* phasor model for the simulation has been used which is the wound rotor asynchronous machine with the positive-sequence. This on grid turbine model is the same which is provided in Matlab-Simulink Simpower System™ library. This *WT* has the *MPPT* system and pitch control. The pitch angle is kept constant at zero degree until the wind speed reaches the point *D* of the tracking characteristics. Beyond the point *D* the pitch angle is proportional to the wind speed deviation from the *D* point. During the simulation, in the operation Control parameters menu, the Var Regulation mode Has been selected, therefor the generated reactive power has been set to be zero, $Q\_ref(pu)=0$

3. SYSTEM SIMULATION IN SIMULINK-MATLAB®

The Simulink implementation of the *LIUC* the model based on equations (8)-(14) is shown in (*Fig.9*)

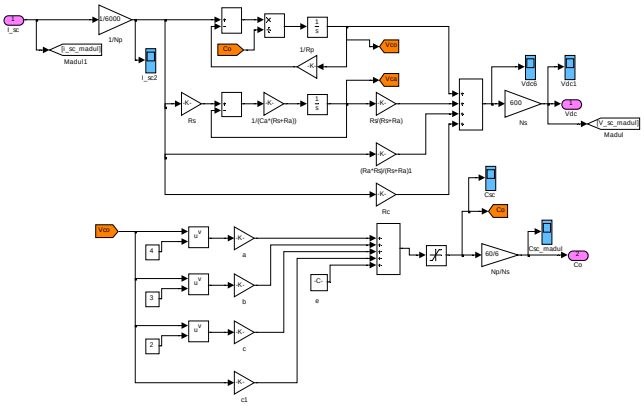

Fig. 9. LITHIUM-ION ULTRA-CAPACITOR BANK SIMULSTION

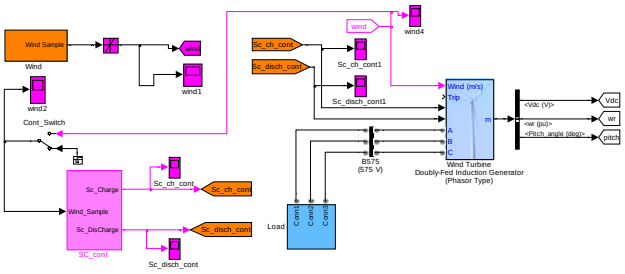

Fig. 10. SIMULATION OF WT ON GRID CONNECTION ULTRA-CAPACITOR CONTROLLER & OBSERVER SYSTEM WITH WIND SIGNAL GENERATOR

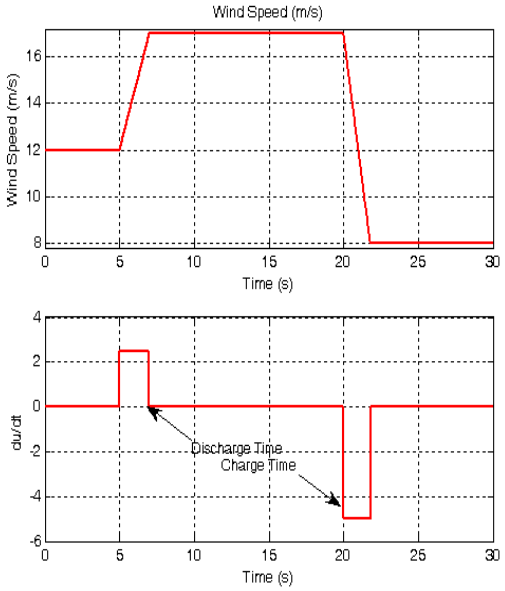

Fig. 11. DETECTION OF WSVS FROM WIND SAMPLE

4. RESULTS AND DISCUSSIONS

The wind speed sample (*Fig.12*) which is produced by wind signal simulator using Band-Limited White Noise is applied to the *VSWT* with a *DFIG* (*Fig.10*) and the results show that *LIUC* used in Proposed *UCESS* could increase the output power of the *DFIG* (*Fig.19*).
The processes of charge & discharge (*Fig.16, 17*) of *UCESB* could help the *MPPT* system to speed up the tracking of the *WSV*s by acceleration of the rotor speed (*Fig.14&15*) and also could correct C_P (*Fig.13*).
Connection of the *UCESB* to the Dc-link causes an increase of the *DC* voltage level form 1200 volts to even more than 1281.4 volts which (*Fig. 16*) is the evidence of this concept.

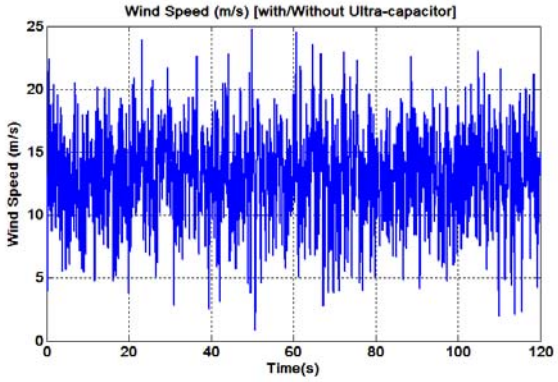

Fig. 12. APPLIED VARIABLE WIND SPEED TO VSWT DFIG ASSOCIATED WITH UCESS

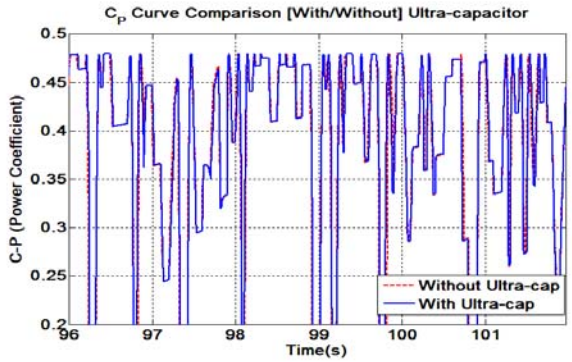

Fig. 13. C_P COMPARISON [WITH/WITHOUT] UCESS

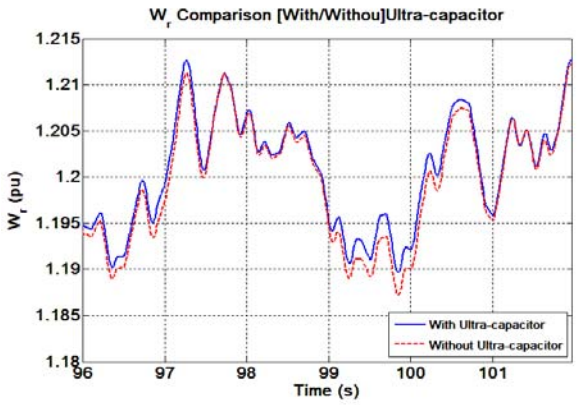

Fig. 14. MAGNIFIED Ω_R COMPARISON [WITH/WITHOUT] UCESS

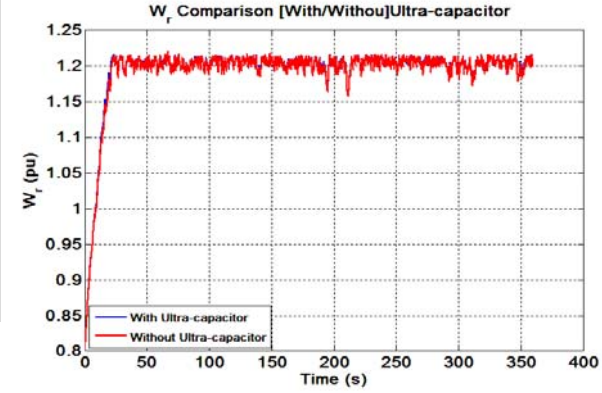

Fig. 15. ω_r COMPARISON [WITH/WITHOUT] UCESS

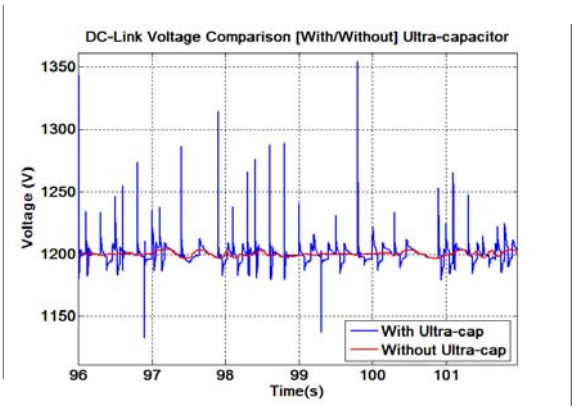

Fig. 16. MAGNIFIED DC-LINK VOLTAGE COMPARISON [WITH/WITHOUT] UCESS

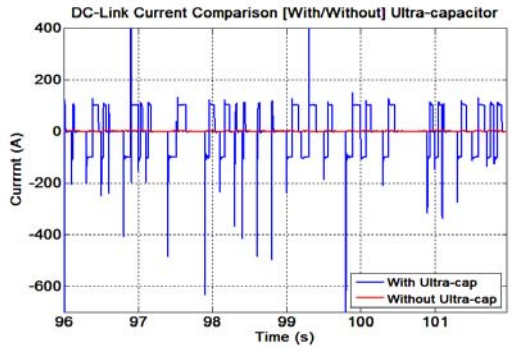

Fig. 17. MAGNIFIED CURRENT COMPARISON [WITH/WITHOUT] UCESS

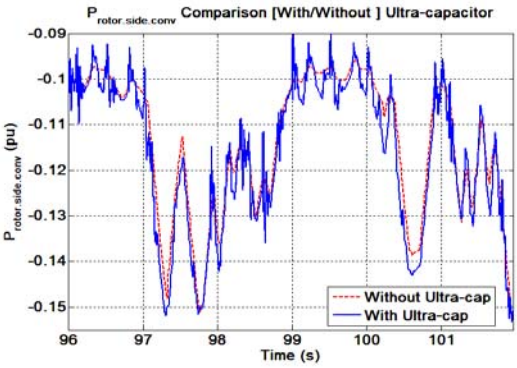

Fig. 18. MAGNIFIDE ABSORB ROTOR POWER INCREASE WITH UCESS COMPARE WITH NO UCEES

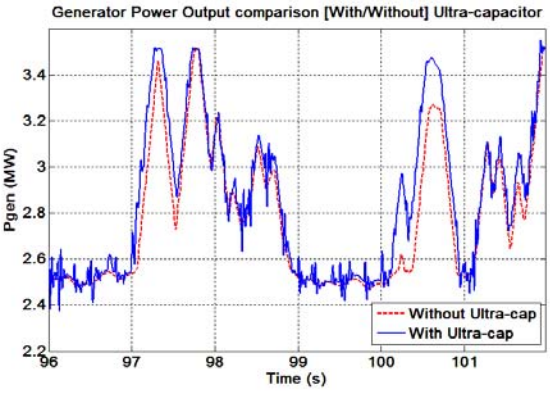

Fig.19. MAGIFIDE DFIG ELECTRICAL POWER OUTPUT INCREASE WITH UCESS UNDER APPLIED WIND SAMPLE

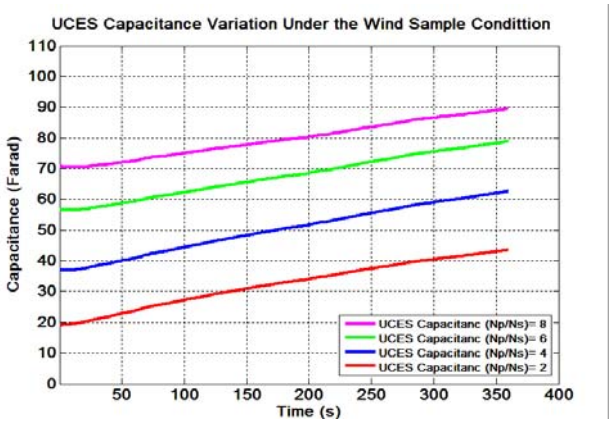

Fig. 20. UCES BANK CAPACITANCE VARIATION UNDER APPLIED WIND SAMPLE THE CONDITION

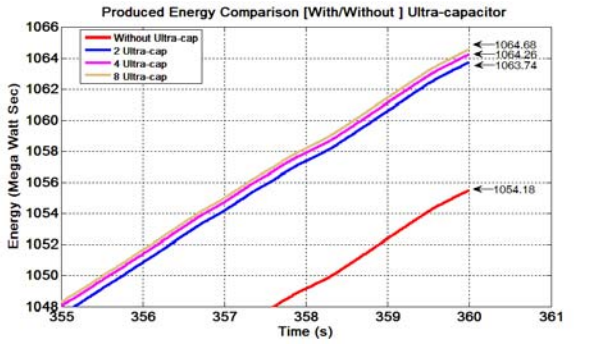

Fig. 21. DFIG ELECTRICAL ENERGY OUTPUT COMPARISON [WITH/WITHOUT UCESS] AND EFFECT OF CAPACITANCE

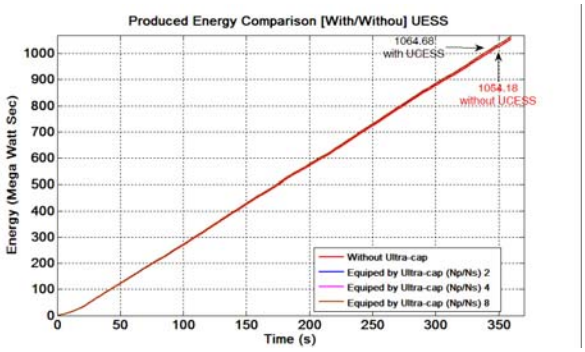

Fig. 22. DFIG ELECTRICAL ENERGY OUTPUT COMPARISON [WITH/WITHOUT] UCESS

TABLE. 5. DFIG OUTPUT ENERGY[MWH] VARIATION WITH DIFFERENT CAPACITANCE OF ULTRA-CAPACITOR

No	N_P/N_S Ratio	C_o (F)	E_{UCES}	E_{Out}
1	0	–	–	$\frac{1054.18 \times 10}{3600}$
2	2	19. 09 –43.35	$\frac{54.65 \times 10}{3600}$	$\frac{1062.78 \times 10}{3600}$
3	4	36.85 –62.43	$\frac{55.11 \times 10}{3600}$	$\frac{1063.49 \times 10}{3600}$
4	6	56.55 – 78.87	$\frac{55.16 \times 10}{3600}$	$\frac{1063.80 \times 10}{3600}$
5	8	70.68 –82.38	$\frac{55.29 \times 10}{3600}$	$\frac{1064.68 \times 10}{3600}$

TABLE. 6. DFIG OUTPUT ENERGY COMPARISON WITH UCESB [(NP/NS=8) &1200-1930VDC&CO=76.755FARAD]

E (Per*)	E_{Net} (MWh)	E_{Out_UCESS} (MWh)	E_{Out_NoUC} (MWh)
*Hour	0.0291	2.9574	2.9283
*Day	0.7	70.9786	70.28
*Month	21	2129.36	2108.36
*Year	255.5	25907.21	25651.71

It is also clear that the Dc-link voltage should be eliminated (for example between two values 1280-1250V) in order to avoid over voltage damages. The (*Fig.17*) illustrates the discharge current of *LIUC* in the Dc-link. To avoid side effects of this discharge current [such as: L(di/dt)] damages it is necessary to eliminate this current (for example ±150A). During the function of *UCESS* the absorbed power by rotor increases (*Fig.18*). As it mentioned in 2.1 the capacitance of *LIUC* is nonlinear (*Fig.20*). According to the (*table.5*) the output power of *DFIG* is proportional to the ratio of *LIUC* capacitance [(N_P/N_S) =2, 4, 6, 8]. The higher capacity causes the higher power (*Fig.20&Fig.21*). Due to what conveys the (*Fig.19*), the *DFIG* electrical output power increases if the proposed system is used. The (*Fig.21&Fig.22*) illustrate that by *VSWT* and *DFIG* without *UCESS* under the wind sample regime could produce 2.928 (*MWh*) while by utilization the proposed *UCESS* [(N_P/N_S) =8, at 1250.6 to 1281.4 *DC Volts*] the output power could increase as much as 2.957(*MWh*). It means 1% increase in power production and if the applied wind sample still the same for 24hours a day, 30 days per month and 365 days per year, the net increased production energy annually would be 255.5 (*MWh*) for a 3.6*MW WT* (*table.6*) and Over production energy of six wind turbine which are equipped with proposed *UCESS* during 20 years could be equal to annual electrical energy produced by one turbine with the same power.

5. CONCLUSION

The new model of smart *UCES* system which is proposed in this paper provides more wind power penetration by increasing a *DFIG* output power driven by the *VSWT* with utilization of Lithium-ion Ultra-capacitors.

It has a substantial impact on the annual energy capture of the *WT*. The *UCESS* control is presented and the system is tested in Simulink-Matlab to examine power increase capability and also the control algorithm of the proposed system and its strategies are described. Several capacitances configurations of *LIUCs* were investigated and their impacts on *WT DFIG* output were shown.

It has been examined that the acceleration and deceleration of *WT* during the wind speed changes can increase electrical output power. Due to no chemical products during charge/discharge, no memory effect and almost no loss in Ultra-capacitors make their life time benefit able. Note that technology development would help to manufacture a very high quality Ultra-capacitors in near future. Despite of the disadvantages *UCES* (mechanical tensions which effect on moving parts, the need of Dc-link voltage elimination); the authors proposed a novel technic by Lithium-Ion *UCESS* to electrical wind power increase which will help more *WTs* penetration in the world. Other advantages of Ultra-capacitors are their low volume, weight and also the small installation footprint. It should be noted that due to there is no moving part in the *UCESS*, their system maintenance is cheap and remember that the nature of *LIUC* short time energy storage in the proposed method is compatible with the nature of wind speed changes.

6. NOMENCLATURE

ρ=Air Density(Kg/m3), A=Area(m^2), V_{Wind}= Wind Speed(m/s), P_m=Mechanical Power (W), C_P=Power Coefficient, R_T=Turbine Blade Radius, ω_T=WT Angular Velocity (AV) (rad/s), ω_r=Rotor AV (rad/s), E_{uc}=Ultra-cap Energy, u_{uc}= Ultra-cap Vlotage (Volts), C_{uc}= Ultra-cap Capacitance(F), $P_{uc.Conv}$=Ultra-cap Power,

β=Pich Angle(dedree), λ=Tip Speed Ratio(TSR), ω_{Opt_ref}=Cont. ref. angular speed

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