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An improved SMC control strategies for PMSG based WECS

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Abstract – *This paper proposes an improved SMC control strategies for Wind Energy Conversion Systems (WECS). A Permanent Magnet Synchronous Generator (PMSG) is connected to the grid through the interface called Diode rectifier, SEPIC converter and a 3-phase Neutral Point Clamped (NPC) inverter and L-filter. This configuration has plenty of features such as simplicity for fraction of kilowatt to few kilowatts. Cheaper than the conventional system and proposed control scheme exhibits good performance even in complicated nonlinear systems such as WECS. The proposed control scheme will reduce chattering issue and also reduce THD. It is the technology that is based on the design of a high speed switching control law that drives the system trajectory onto a user chosen Hyperplane. Further use of 3-phase Neutral Point Clamped will further reduce THD and use of SEPIC converter will increase Low Voltage Ride Through (LVRT) capacity. The adequacy of the proposed control methodology is investigated by the simulation results in Matlab.*

Keywords – ***Wind Turbine, Permanent Magnet Synchronous Generator (PMSG), SEPIC Converter, Neutral Point Clamped (NPC), Sliding Mode Control (SMC), Low Voltage Ride Through (LVRT), Generator Control, Converter Control.***

I. INTRODUCTION

Sustainable Energy source has been considered as an option vitality source since petroleum derivatives are restricted and make atmosphere contamination issues. WECS is the most favorable sources of Sustainable Energy. Because Several innovations were made to enhance this technology from the capacity of few tens of kilo Watts to several mega Watts over the past few decades. But it poses lot of issues to maintain good quality of power. One of them is operation of wind turbine system in low voltage ride through (LVRT) which rises during fault condition. So wind turbine systems are required to stay connected to the grid during grid faults with considering Voltage drop level and Voltage-Time profile. Another aspect is system protection. It is assumed while designing the distribution system that unidirectional power flow from sending end of feeder to the receiving end. Mean while addition of Renewable energy sources (RES) and Distributed generators (DG) to the distribution feeders will provide additional sources for feeding fault current. Sustainable Energy source integration in power framework raises a great deal of difficulties in research and in practice [1] [2]. Now days WECSs furnished with Permanent Magnet Synchronous Generator (PMSG) are getting more prominent in wind energy community particularly in offshore applications because of the disposal of gear box and excitation system [3].

In PMSG based WECS, the generator is directly connected to the utility grid through a power converter. Numerous power electronic converter configurations have been incorporated in wind energy applications. Among them multilevel converter such as 3-phase Neutral Point Clamped (NPC) is becoming more popular in the applications such as grid-tied. Because it outputs more voltage level with less switching losses [4][5]. These merits of NPC converter make it guaranteed to exchange the electrical energy at low to medium voltage with lower current, less paralleled devices, and reduce size of filter in correlation with two-level converter[6][7]. Large size system suffers from problems related to frequency and voltage at the point of common coupling (PCC).

Most of the researches in the area of WECS were focused on the improvement of control strategies to increase its ability to supply and regulate active and reactive power in both offline & online grid applications [8]. These control approach is to reduce generator current and extract maximum power from WECS, to keep DC-link voltage constant and control the reactive power injected in to the grid.

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Apart from the above features it decreases harmonic current at PCC. These control procedures of PMSG wind turbines can be organized into two types. The first one is Maximum Power Point Tracking (MPPT) is achieved by Machine Side Converter MSC and DC-Link voltage is controlled by GSC. The second control strategies is MPPT is achieved by GSC and DC-Link voltage is controlled by MSC [15]. In both cases, vector control is used to accomplish control objectives. Different control schemes have been developed to achieve the control objectives of PMSG based WECS operation. Three prevalent methods being used to achieve the control goals are: Zero d-Axis Current (ZDC) control, Maximum Torque per Ampere (MTPA) control, and Unity Power Factor (UPF) control.

Researchers have developed different linear control schemes to grid connected inverter but it suffers from demerits such as incapability to track sinusoidal trajectory and poor noise rejection capability [10][11]. So it leads to the development of nonlinear techniques to the grid-tied applications [12]. But these methods are sensitive to modeling errors and difficult to implement [13][14]. On the other hand sliding mode control(SMC) become popular due to its robustness and order reduction , almost insensitive to parameter variations and converges in finite time with good dynamic characteristic that too it is applicable for both linear and nonlinear applications[15][16]. The main disadvantage of SMC is that it suffers from chattering phenomenon due to discontinue function in SMC. So it leads to further development of different control schemes to reduce chattering issue. Constant reaching law is modified to Adjustable reaching law (ARL) [16]. An exponential term is placed instead of constant reaching law which further reduces the chattering phenomenon and improves THD at PCC.

ARL perform controller gain correction based on error signal generated between the actual and desired system states. As the error is high then controller gain will be high so that system state moves faster towards desired state. When the error is small then corresponding gain will be less and system state moves slower towards desired state. When the error is zero then the system is at the desired state and gain is zero. But this control approach does not change the gain in an astute way in the extensive variety of error values from zero to high error quantities. So in this paper we enhanced the exponential reaching law by changing the control signal. The major contribution of this paper is the propose control scheme reduces the reaching time of

The system trajectories to the equilibrium point even the initial condition of the system parameters are far from the sliding surface. It further mitigates chattering issue and improves current THD. This paper is organized as takes after. A short audit of SMC hypothesis and EERL is introduced in segment II. In segment III, displaying of PMSG wind turbine and its components are clarified. Proposed control conspire is based on sliding mode approach is depicted in area IV. Numerical reenactment and exploratory outcomes are accounted for in area V. At long last, area VI closes the synopsis of key components of the proposed controller.

II. SLIDING MODE CONTROL THEORY BASED ON MODIFIED REACHING LAW

Sliding-mode control depends on the outline of a fast switching control law that drives the framework's direction onto a client picked hyperplane in the state space, otherwise called sliding surface. The key thought of the sliding-mode hypothesis is to bring the investigation of an nth-order framework to that of a first-order one by considering just the sliding function and its derivatives as the new state variables. Let us consider a second-order system.

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = f(x_1, x_2) + b(x_1, x_2).u$$

Where f,g are both nonlinear functions in terms of x_1, x_2. We have to design a state feedback control law to stabilize the origin. Suppose we can design a control law that contains the motion of the system to the surface S= $a_1x_1 + x_2=0$ on this surface the motion is governed by $\dot{x}_1 = -a_1x_1$. If $a_1>0$ then $x(t)$ tends to zero as t tends to infinity and the rate off convergence can be controlled by the choice of a_1. The motion in the surface S=0 is independent of h and g. So how can we bring the trajectory to the surface S=0 and maintain it there?

$$\dot{S} = a_1 x_2 + h(x) + g(x).u \tag{1}$$

S dynamics in Eq.(1) a candidate lyapunov function is introduced taking form.

$$V = 1/2 * S^2 \tag{2}$$

In order to provide the asymptotic stability of the Eq.(1). About the equilibrium point S=0 the following conditions must be satisfied. (a) $\dot{V}<0$ for all $S\neq 0$. (b) $\lim_{|S|\to\infty} V = \infty$ and it is satisfied by Eq.(2) and by lyapunov exponential stability theorem.

$$\dot{V} \leq -\alpha V^{1/2} \qquad \alpha > 0 \tag{3}$$

$$V^{1/2}(t) \leq -1/2\alpha t + V^{1/2}(0)$$

Consequently V(t) reaches to zero in a finite time t_r that is bounded by

$$t_r \leq 2\, V^{1/2}(0) / \alpha$$

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so a control u that is computed to satisfy Eq.(3) will drive the variable S to zero in finite time and will keep it at zero thereafter.

This scheme has drawback such as switching control is not instantaneous and the sliding surface in not rigorously known so it leads to high control activity then required which makes the input as well as output chattering. Numerical model of real time plants are constantly uncertain. This jumble can be produced because of parametric uncertainties and unmodeled dynamics. In this way a control framework is should have been vigorous to these errors to have the quality of keeping the framework performance stable. Sliding mode control is an intense strong control technique for uncertain frameworks that has been generally examined in both theoretical and industrial application aspects [16]. To do so a new approach called enhanced exponential reaching law (EERL) was proposed. Let us reconsider SMC for new terminology.

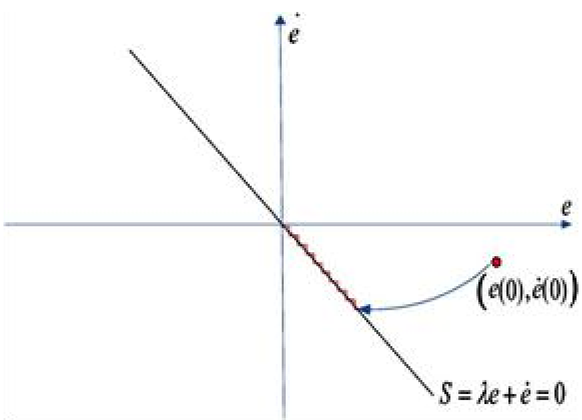

Fig.1 Sliding-mode mechanism in phase plane

$$\ddot{x} = f(x,\dot{x}) + g(x,\dot{x})u \qquad (4)$$

Where *x* and *u* are state and input vectors, and f and g are bounded nonlinear matrix functions of the system states. It is supposed that function g is continuous and invertible. The control aim is to get the state vector to track the desired state vector in the presence of disturbances and uncertainties. Let $\tilde{x} = x - x_d$ be the trajectory error in state vector *x*, where x_d is desired state vector. Conventionally, time-varying sliding Surface for a nth order system is chosen as

$$S(t) = \left(\frac{d}{dt} + \Lambda\right)^{n-1}(x - x_d) \qquad (5)$$

Where Λ is a strictly positive number. For second order systems, one can define following surface.

$$S(t) = \Lambda\tilde{x} + \dot{\tilde{x}} \qquad (6)$$

Therefore, the problem of tracking the desired vector is equivalent to keeping S at zero all the times. In fact, there are two different modes in SMC methodology. In reaching stage, tracking error vector $\tilde{x}$ is reached to the sliding surface S = 0 in a finite time. Since sliding surface is an invariant set, system trajectory slides and remains on S = 0 in sliding stage. It is worth mentioning that S can be selected as x-x_d for first order systems

$$\frac{1}{2}\frac{d}{dt}S^2 \le -\eta|S| \qquad (7)$$

Where η is a strictly positive constant. Satisfying above condition keeps the system trajectories remaining on the sliding surface. Sliding condition (7) can be expressed as

$$S\dot{S} \le 0 \qquad (8)$$

Integrating Eq. (7) we get

$$t_{reach} \le \frac{|S(t=0)|}{\eta} \qquad (9)$$

Where t_{reach} reaching time, is the required time for $\tilde{x}$ to reach the sliding surface. With the purpose of satisfying expression (8), $\dot{S}$ is generally taken as

$$\dot{S} = -K\,\mathrm{sign}(S) \qquad (10)$$

Where sign is the sign function and K is also a positive constant. Choosing K large enough guarantees sliding condition in constant rate reaching law SMC. To satisfy sliding condition despite uncertainty in the system, a discontinuous term can be added to control input. Accordingly our control input takes the form

$$u = u_{con} + u_{discon} \qquad (11)$$

Therefore, it is as follows

$$u = g^{-1}(-f + \dot{x}_d - \Lambda\tilde{x} - k\,\mathrm{sign}(s)) \qquad (12)$$

Clearly control law is made out of two terms. Discontinuous term which is applied because of imprecision of framework modeling and disturbances prompts an undesired marvel called chattering. Chattering may fortify overlooked high recurrence flow of the system model. Picking proper estimation of K would be an exchange off between achieving time and level of chattering. This technique is called CRL sliding mode approach. A few works are done to weaken or dispense with the jabbering issue by altering achieving law. In [16] they proposed constant-proportional rate reaching law and power rate reaching law. Constant-proportional rate reaching law has the form

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$$\dot{S} = -\wedge S - K\text{sign}(S) \quad (13)$$

Definite integration of (13) between zero and t_{reach} leads to

$$\int_{S(t=0)=s0}^{S(treach)} \frac{dS}{\wedge S + Ksign(S)} = \int_0^{treach} -dt \quad (14)$$

Note that $S(t_{reach}) = 0$. For $S \geq 0$, reaching time is

$$t_{reach} = \frac{1}{\wedge} \ln \frac{\wedge S0 + K}{K} \quad (15)$$

If $S \leq 0$, it yields

$$t_{reach} = \frac{1}{\wedge} \ln \frac{-\wedge S0 + K}{K} \quad (16)$$

Therefore, one can simply express the reaching time in all conditions as

$$t_{reach} = \frac{1}{\wedge} \ln \frac{\wedge|S0| + K}{K} \quad (17)$$

The main disadvantage of (13) is that reaching law is not adjustable. Power rate reaching scheme is as

$$\dot{S} = -K|S|^{\gamma_x}\text{sign}(S) \quad (18)$$

Where $0 < \gamma_x < 1$ and $k > 0$. By applying the same
Procedure as explained before, the reaching time is as

$$t_{reach} = \frac{1}{(1-\gamma_x)K} |S_0|^{(1-\gamma_x)} \quad (19)$$

The demerit feature of (18) is the reduction of its robustness due to the rapid lessening of the exponential term$|S^{\gamma}|$. In [16], an additional term is introduced to reduce chattering problem in robot applications by defining following function to handle
Reaching law

$$\dot{S} = -\frac{K}{D(S)} \text{sign}(S) \quad (20)$$

Where

$$D(S) = \alpha + (1-\alpha)e^{-\beta_x|S|} \quad (21)$$

In Eq.(18) $0 < \alpha < 1$ and $\beta_x > 0$ This method is called Exponential Reaching Law (ERL) approach. The reaching time for ERL is obtained as

$$t_{reach} = \frac{1}{K} \left(\alpha|S_0| + \frac{(1-\alpha)}{\beta_x} [1 - e^{-\beta_x|S_0|}]\right) \quad (22)$$

This method brings a lot of advantages such as gain adaptation based on the position of S_0 regarding the sliding surface, smaller reaching time and chattering reduction but shows a higher THD than our proposed method which might cause problem in power electronics application. To solve above mentioned issues, an EERL is applied which is a combination of different concepts in [15] and [16] as well as applying new structure for managing the reaching law in both reaching and sliding stages. Our proposed EERL is as follows

$$\dot{S} = -\wedge S - \frac{K}{D(S)} |S|^{\gamma_x} \text{sign}(S) \quad (23)$$

if $|S|$ raises, D(S) goes towards α, then coefficient of sign function would be $K|S|^{\gamma_x}/\alpha$. In contrast when $|S|$ reduces, it tends to $K|S|^{\gamma_x}$. This phenomenon makes the controller gain to be modified between $K|S|^{\gamma_x}$ to $K|S|^{\gamma_x}/\alpha$. therefore, it adjusts the reaching
time to approach to the sliding surface. In other words, EERL approach specifies faster reaching speed or smaller reaching time with respect to the constant rate reaching law SMC considering similar gain K. In addition, existence of ∧ and γ_x along with D(S) simultaneously in the controller will augment the characteristics of the controller while eliminating
the disadvantages of each approach.

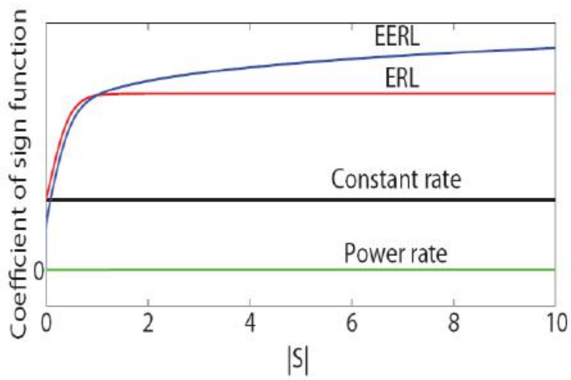

Fig. 2. Sign coefficient comparison based upon different sliding mode control methods.

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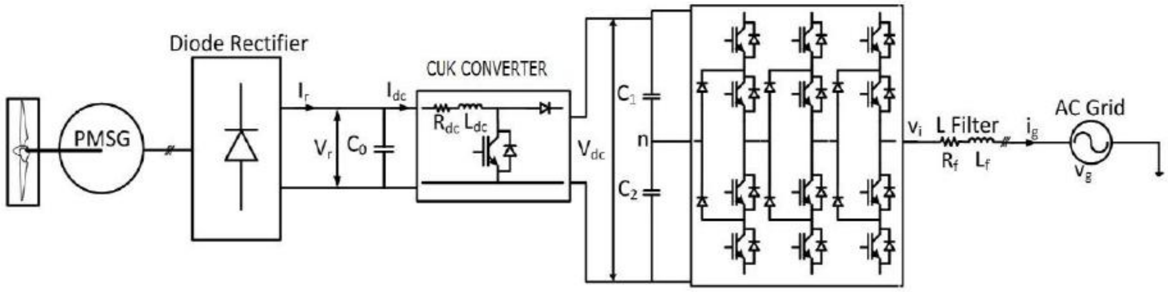

Fig.3 General Overview of grid connected PMSG.

III. DYNAMIC MODEL OF THE PMSG BASED WIND TURBINE

This area quickly clarifies components of the framework and gives their administering conditions. Fig. 3 exhibits the general review of network associated PMSG based WECS. The streamlined torque is made by force acting up on the sharp edges is transferred to PMSG via the drive train. At that point PMSG changes over the mechanical energy into electrical energy. This energy is infused to the framework through diode rectifier, support converter, NPC inverter and L channel to meet the required objectives. This topology is utilized as a part of both low and medium voltage applications [17][18][19]. The advantages of this scheme are: simple control and system cost reduction. The theoretically available power in the wind can be stated as

$$P_{available} = \frac{1}{2}\rho A v_w^3 \quad (24)$$

where ρ, v and A are the air density (kg/m^3), the wind speed (m/s) and the swept area of rotor blades (m^2), respectively. Due to physical limits, wind turbine blades only transfer portion of the wind kinetic energy. The absorbed mechanical power by rotor is given by the following expression

$$p_t = \frac{1}{2}\ \pi\ \rho\ R^2\ v_w^3\ C_p(\lambda, \beta) \quad (25)$$

Where C_p is power coefficient. In WECS aerodynamics, there are two main variables that make C_p change: blade pitch angle β and tip speed ratio (TSR) of the blade $\lambda = R\ w_{rm}/\ v_w$ in which R and w_{rm} are the rotor plane radius and the angular velocity of the rotor, respectively. A one-mass drive train model is chosen in this paper to simplify state space model of the system.

In WECS the generation capacity is specified by using the generator output versus actual wind speed curve. The operating range of WECS is between the cut -in ($v_{w\text{-}min}$) and cut-out ($v_{w\text{-}max}$). WECS can be operated in four different regions. When the wind speed is below cut-in speed it operates in region-I. When the speed is in between cut-in speed to the rated speed then WECS will operate in region-II. When the speed is between rated speed and cut-out speed then WECS will operate in region-III. When the speed is above cut-out speed it will operate in region-IV.

$$P_t = \frac{1}{2}\pi\rho R^3 v_w^3 C_{p\text{-}max} \quad (26)$$

In the wind speed higher than rated wind speed value and lower than $v_{\omega-max}$ (region III), the WECS power curve remains constant at rated power. Therefore the wind turbine must operate with power coefficients lower than C_{p-max}. Fig. 3 demonstrates power curve of a typical wind turbine in which working regions are explicitly shown. To investigate wind turbine dynamic behaviour, it is necessary to model other components of the WECS. Dynamic model of the surface mounted PMSG in *dq* rotor reference frame is well-studied in the literature [9].To model SEPIC converter, following equations are used

$$\frac{dI_{dc}}{dt} = -\frac{R_{dc}}{L_{dc}} I_{dc} + \frac{1}{L_{dc}} V_r - \frac{(1-q)}{L_{dc}} V_{dc} \quad (27)$$

$$\frac{dV_r}{dt} = \frac{1}{C_0} I_r - \frac{1}{C_0} I_{dc} \quad (28)$$

Where R_{dc} and L_{dc} are resistance and inductance of SEPIC converter, V_r and I_r are the rectifier output voltage and

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current, V_{dc} is the DC link voltage, $0 \le q \le 1$ is the duty cycle used for generation of switching signal, and I_{dc} is the inductor current. It must be mentioned that V_{dc} as a system state is controlled by grid currents in our study .The equations of L filter in synchronous reference frame are as

$$\frac{di_{dg}}{dt} = -\frac{R_f}{L_f}\, i_{dg} + \frac{1}{L_f}\, v_{ds} - \frac{1}{L_f}\, v_{dg} + w_g\, i_{qg} \quad (29)$$

$$\frac{di_{qg}}{dt} = -\frac{R_f}{L_f}\, i_{qg} + \frac{1}{L_f}\, v_{qs} - \frac{1}{L_f}\, v_{qg} + w_g\, i_{dg} \quad (30)$$

Where R_f and L_f are resistance and inductance of the filter, v_{dg} and v_{qg} are grid voltages, v_{di} and v_{qi} are NPC inverter output voltages, di_{dg} and di_{qg} are grid currents, and ω_g is the grid angular velocity.

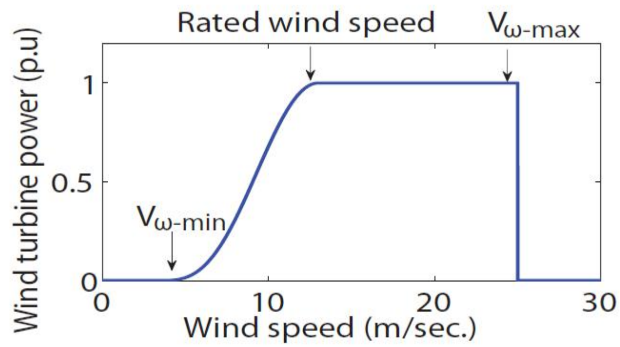

Fig. 4 Typical power curve of wind turbine system

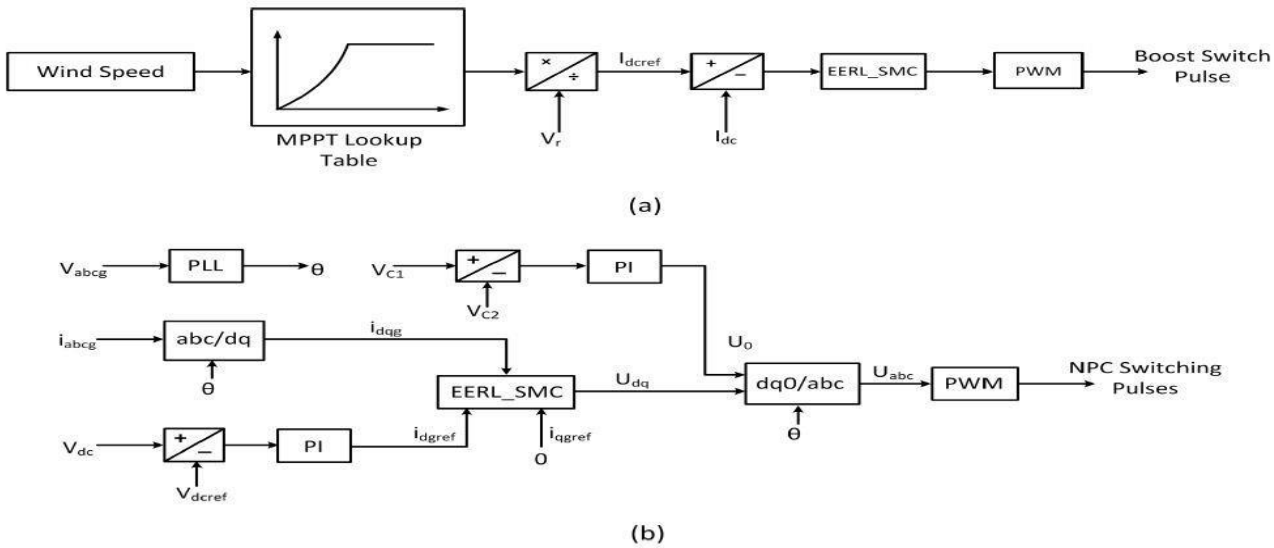

Fig.5 SMC based EERL approach for: (a) SEPIC converter control, (b) NPC inverter control.

IV. CONTROLLER DESIGN FOR PMSG WIND TURBINE

In order to control PMSG based WECS, it is required to generate appropriate switching signals for SEPIC converter and NPC inverter based on the PMSG parameters and connection point requirements. Our proposed sliding mode controller based on EERL considering the first order dynamics has the following structure

$$u = g^{-1}\left(- f + \dot{x}_d - \wedge S - \frac{K}{D(S)}\, |S|^{\gamma_x}\, \mathrm{sign}(S) \right) \quad (31)$$

This expression can be applied to every system with governing equation similar to (1), considering the availability of inverse of g function. Noticeably, there exists inverse functions of the above-mentioned equations of PMSG based WECS components. It is employed to generate duty cycles for SEPIC converter and NPC inverter switches. Based on Fig. 3, essential input and state vectors are as follows

$$x = [\, V_r\, I_{dc}\, V_{dc}\, i_{dg}\, i_{qg} \,] \quad (32)$$

$$u = [\, q\; v_{dc}\; v_{qs} \,]^T \quad (33)$$

where superscript T indicates transposition of the matrix.

As diode rectifier is not a controllable converter, generated power by PMSG can be controlled by I_{dc}[38]. To control

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SEPIC converter, Eq. (28) is considered. Based on EERL sliding approach, the final control input is as

$$q = \frac{R_{dc}}{V_{dc}} i_{dc} + \frac{(V_{dc} - V_{dc0})}{V_{dc}} + \frac{L_{dc}}{V_{dc}} \frac{di_{dc-ref}}{dt} - \frac{L_{dc}}{V_{dc}} \Lambda_{dc} S_{dc}$$

$$- \frac{L_{dc}}{V_{dc}} \frac{K_{dc}}{D_{dc}(S_{dc})} |S_{dc}|^{\gamma_x} \operatorname{sign}(S_{dc}) \qquad (34)$$

Where $S_{dc} = i_{dc} - i_{dc}-ref$ and $D_{dc}(S_{dc}) = \alpha_{dc} + (1 - \alpha_{dc})e^{-\beta dc|Sdc|}$. In (31), V_{dc} has to be controlled such that it is a constant voltage. Desired current of L_{dc} is obtained by MPPT scheme of PMSG. Various MPPT algorithms for PMSG based WECS have been proposed. In this paper, TSR control is chosen for the MPPT algorithm in which ω_{rm-ref} is obtained using $v_w\lambda_{opt}/R$. Optimum value of TSR is the point that maximizes power coefficient. Commonly, following generic expression is used to model the WECS efficiency for extracting mechanical energy from wind kinetic energy.

$$C_p(\beta, \lambda) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^x - C_5\right) e^{C_6/\lambda_i} + C_7\lambda \qquad (35)$$

With

$$\frac{1}{\lambda_i} = \frac{1}{(\lambda + 0.08\beta)} - \frac{0.035}{\beta^3 + 1} \qquad (36)$$

where the coefficients c_1 through c_7 and x are just the C_p curve fitting coefficients. Consequently, SEPIC converter control diagram method is depicted in Fig. 5(a). To control NPC inverter, our goal is to obtain unity power factor for grid-tied inverter. Hence, quadrature current injected to grid is set to be zero.

Considering the L filter state space Eqs. (29) and (30), the control signals in dq reference frame are

$$V_{di} = R_f i_{dc} - L_f w_g i_{qg} + v_{dg} + L_f \frac{di_{dg-ref}}{dt} - L_f \Lambda_d S_d$$

$$-L_f \frac{K_d}{D_d(S_d)} |S_d|^{\gamma} \operatorname{sign}(S_d) \qquad (37)$$

$$V_{qi} = R_f i_{qc} - L_f w_g i_{dg} + v_{qg} + L_f \frac{di_{qg-ref}}{dt} - L_f \Lambda_q S_q$$

$$-L_f \frac{K_q}{D_q(S_q)} |S_q|^{\gamma} \operatorname{sign}(S_q) \qquad (38)$$

Where $S_d = i_{dg} - i_{dg-ref}$, $S_q = i_{qg} - i_{qg-ref}$, $D_d(S_d) = \alpha_d + (1 - \alpha_d)e^{-\beta|S_d|}$ and $D_q(S_q) = \alpha_q + (1 - \alpha_q)e^{-\beta|q|}$ NPC control approach is shown in Fig. 5(b).If we suppose that quadrature component of grid voltage, v_{qg} is equal to zero, and also having unity power factor $i_{qg} = 0$, then active and reactive power injected to the grid based on synchronous dq reference frame are 3/2 $v_{dg}i_{dg}$ and 0 respectively. Therefore, direct and quadrature components control of grid current leads to active and reactive power control of WECS. This implies that DC link voltage must be kept constant and regulated. Desired value of direct-axis current of grid is acquired by PI controller of DC link voltage.

V. SIMULATION RESULTS

The target of grid-connected renewable energy system such as WECS is to transfer maximum power into the grid with UPF because poor power factor on the power network increases power line losses and makes it very difficult to keep the voltage regulated. Voltage and current waveforms of phase (a) at PCC as well as a closer observation of them are demonstrated in Fig. 6. It should be noted that current waveforms have been enlarged and multiplied by a constant to be seen more easily. One salient objective of the controller in WECS is to obtain unity power factor. From Fig. 6, it is clear that in steady state, Current at the grid is in phase of voltage at all wind speeds.

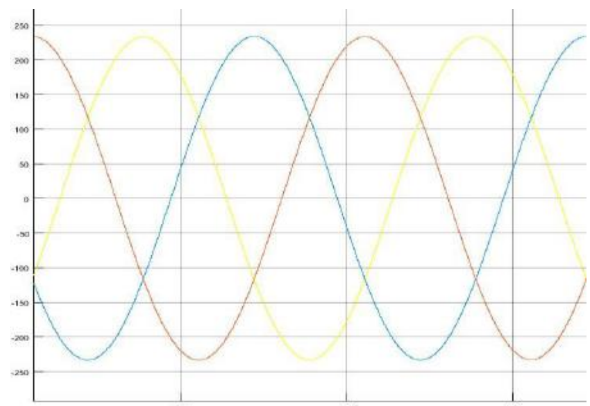

Fig 6.(a) output voltage at PCC

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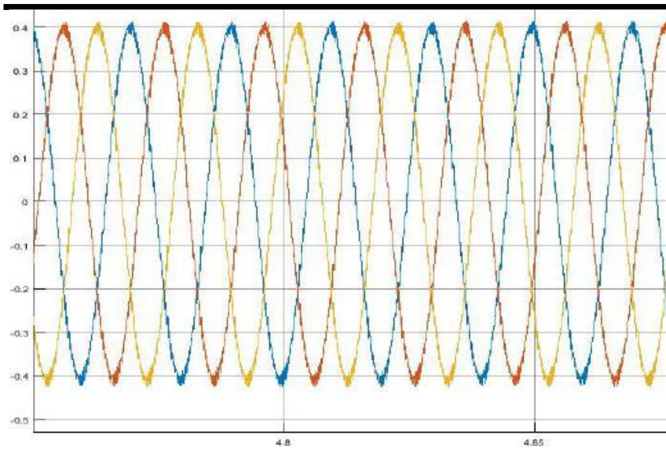

Fig 6.(a) output current at PCC

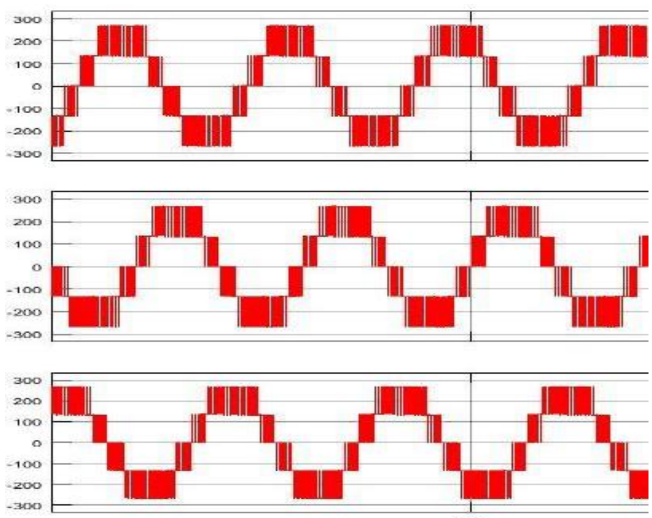

Fig 7. Inverter output voltage

VI. CONCLUTION

In this paper EERL was proposed and investigated on the grid connected PMSG wind turbine system through Matlab and simulation results were presented in this paper. This configuration is best suitable for low & medium power applications. This topology exhibited excellent dynamic error tracking error and minimized THD & chattering issue at PCC.

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