PERMANENT MAGNET SYNCHRONOUS GENERATOR WIND ENERGY SYSTEM OPERATION WITH FUZZY LOGIC CONTROLLER FOR MAXIMUM POWER POINT TRACKING TO IMPROVE POWER QUALITY

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***Abstract*—This paper presents an adaptive maximum power point tracking (MPPT) algorithm for small-scale wind energy con- version systems (WECSs) to harvest more energy from turbulent wind. The proposed algorithm combines the computational behav- ior of hill climb search, tip speed ratio, and power signal feed- back control algorithms for its adaptability over wide range of WECSs and fast tracking of maximum power point. In this paper, the proposed MPPT algorithm is implemented by using buck– boost featured single-ended primary inductor converter to extract maximum power from full range of wind velocity profile. Experimental results show that tracking capability of the proposed algorithm under sudden and gradual fluctuating wind conditions is efficient and effective.**

***Index Terms*— Maximum power point tracking, hill climb search algorithm, tip speed ratio algorithm, power signal feedback al- gorithm, single-ended primary inductor converter (SEPIC) dc-dc converter.**

I.INTRODUCTION

Interest in renewable energy is increasing as alternative energy source to conventional fossil fuel, because of latter's soaring prices, limited reserve capacity, and environmental concerns. Across the globe, research community is exploring all possibilities for the efficient energy conversion from freely available abundant renewable energy sources. Among the pop- ular renewable energy sources, wind energy is gaining more support due to its less space occupancy and zero-carbon emis- sion during operation. Variable speed wind energy conversion systems (WECSs) can harness more electrical energy than fixed speed WECSs by controlling their speed according to the varia- tions in wind velocity [1], [2]. Maximum power point tracking (MPPT) algorithms are used to extract maximum power from the available wind energy and they are classified into three cat- egories, namely tip speed ratio (TSR) control, power signal feedback (PSF) control and hill climb search (HCS) control [3]. In TSR control method, rotational speed of the wind generator (WG) is regulated in order to maintain the TSR to an optimum value at which power extraction is maximum. Optimal speed for the turbine ω_m^* (rad/s) is calculated by using wind velocity V_w (m/s), turbine rotating speed ω_m (rad/s), and optimal TSR λ_{opt} of the system as follows [4]–[6],

$$\omega_m^* = \frac{\lambda_{\text{opt}} V_w}{R} \tag{1}$$

where R is rotor radius in meter. Implementation of TSR algorithm requires the knowledge of λ_{opt} of the turbine and is system dependent.

In PSF control method, wind turbine operates at optimal operating point by using the prior knowledge of turbine's maximum power curve [7]–[10]. Implementation of this method requires the prior knowledge of maximum power curves which can be obtained through off-line experiments or system simulations. In HCS control method, an arbitrary small perturbation is given to one of the independent variables of the system and next pertur- bation is decided based on the changes in output power due to preceding perturbation [11], [12]. Drawbacks of this algorithm are, slow tracking response, especially for high inertia systems. Advanced HCS based on-line training algorithms are reported in [13] and [14] to improve the system tracking response of its maximum power point (MPP). In the present work, a simpli- fied algorithm than [14] has been implemented to improve the system tracking response under rapid fluctuating wind velocity conditions.

Microgrid is essentially a collection of distributed energy resources (DERs), potential energy storage devices, and loads connected together to form a relatively small-size distribution network [15]. Small-scale WECSs are main resources for DERs in microgrid systems and are usually installed at congested places with turbulent wind conditions where wind speed and direction vary frequently. Extraction of maximum power with fast tracking control strategy under fluctuating wind conditions is a challenging issue. In small-scale WECSs, power conditioing converter's control is most frequently adapting strategy to extract maximum power since pitch angle control is impractical due to their mechanical structure. In this work buck-boost fea- tured single-ended primary inductor converter (SEPIC) dc–dc converter has been used to extract maximum power from total range of wind velocity profile.

II.SYSTEM CONFIGURATION AND MODELING

In the process of developing a laboratory-scaled dc micro grid platform, WECS related system configuration is shown in Fig. 1. In small scale variable speed WECS, direct driven permanent magnet synchronous generator (PMSG) with diode rectifier is the most preferred configuration due to PMSG's high air-gap flux density, and high torque-to-inertia ratio. Its decoupling control performance is much less sensitive to the parameter in variations of the generator.

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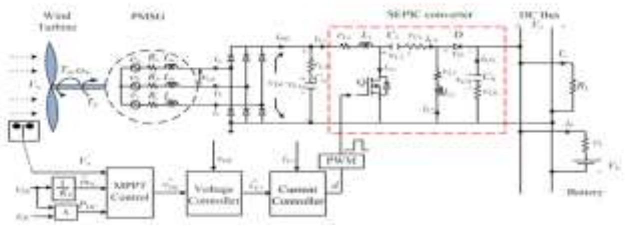

Fig 1.WECS CONVERTION

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A.Wind Turbine Aerodynamic Model

Mechanical output power P_m extracted from wind by the wind turbine and corresponding torque T_m imparted onto WG can be modeled as [20],

$$P_m = \frac{1}{2}\rho\pi R^2 V^3 C_p(\lambda, \beta)$$

$$T_m = \frac{P_m}{\omega} \qquad (2)$$

where ρ is air density (kg/m^3), C_p is power coefficient which is function of TSR λ and pitch angle β. The coefficient, C_p can be modeled by using rotor blade's aerodynamic design principles [21],

B .PMSG-Diode Rectifier

*Model*Induced emf, e_s (V), in stator winding of PMSG, when it is subjected to a constant flux, φ (Wb), while rotating with a speed,

ω_m (rad/s), is given by

$$e_s = k\,\omega_m = k\frac{\omega_e}{P} \qquad (4)$$

where k (V s/rad) is machine induced voltage constant, P is total number of rotor pole pairs and ω_e is electrical angular frequency of PMSG stator induced voltage.

Assuming that both the commutating angle and commutating inductance are negligible, the relation between diode rectifier output voltage, V_{DC} and line voltage at terminals of PMSG.

Wind turbine rotor speed can be controlled by controlling the generator torque as follows

$$\omega_m = \frac{T_m - T_g}{B_t} \qquad (9)$$

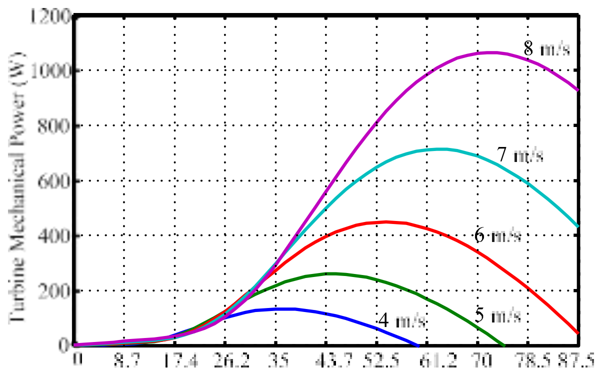


Fig. 2. MPPT converter input voltage and turbine power characteristics.

III.ADAPTIVE MPPT CONTROL ALGORITHM

At constant wind velocity, wind turbine output power becomes function of power coefficient (2), and at constant pitch angle, power coefficient becomes function of rotor speed as given in (1) and (3).From this discussion,condition for MPP can be obtained as

$$\frac{dP_m}{d\omega_m} = 0. \qquad (12)$$

Applying the chain rule [11], (12) can be written as follows,

$$\frac{dP_m}{d\omega_m} = \frac{dP_m}{dv_{DC}} \cdot \frac{dv_{DC}}{d\omega_e} \cdot \frac{d\omega_e}{d\omega_m} = 0. \qquad (13)$$

It can be concluded by using (4)–(6),

$$\frac{dP_m}{d\omega_m} = 0 \Leftrightarrow \frac{dP_m}{dv_{DC}} = 0. \qquad (14)$$

Relation between turbine output power and rectifier output voltage is shown in Fig.2. It is observed that this relation has a corresponding single optimal V_{DC} value for every wind veloc- ity and objective of the proposed algorithm is to search for this optimal operating point v_{DCopt}.

Flowchart of the proposed MPPT algorithm is shown inFig. 3. Turbine rotor radius R and electro motive force (emf) constant K_b (V s/rad) can be obtained from wind turbine specifications report and open circuit characteristics of WG respectively. Implementation of the algorithm requires a dynamically programmable memory to store system's optimal characteristics in the form of a lookup table and a single- dimensional array. Lookup table holds the optimal relation between wind velocity-optimal dc voltage-maximum output power (V_w - v_{DCopt} -P_{DCmax}) and single-dimensional array keeps the optimal TSR value, λ_{opt}, of the system. Wind velocity col- umn will act as index for the lookup table. Size of the lookup table is limited by the range of the wind velocity and size of the optimal TSR vector is limited to 100 entries. Operating wind velocity range, 3–8 m/s, is written into the index column of the lookup table with the difference of 0.25 m/s between two sequential entries. Initially, all values of v_{DCopt} and P_{DCmax} in the lookup table are initialized to zero and first entry of optimal TSR vector, $\lambda_{opt}[1]$, is initialized with a good guess value of 7 [26]. Algorithm reads wind velocity, SEPIC's input voltage and input current for every 10 ms of sampling time. This sampling frequency of the algorithm is adequately chosen based on the dynamics of the wind turbine. If the difference between two consequent samples of wind velocity is within 0.25 m/s, the algorithm treats that the wind is steady wind otherwise turbulent wind.

During steady wind, as described in flowchart, based on the changes in output power with respect to the changes in control variable, algorithm provides reference signal $v_{DCref}(k + 1)$ by implementing HCS control algorithm. Meanwhile, algorithm performs memory updating computations to optimize the existing data of the lookup table and optimal TSR vector. If the turbine extracts more power compared to previous iteration During turbulent wind conditions, algorithm provides reference signal by implementing either PSF or TSR algorithmic computations. Algorithm searches the lookup table for v_{DCopt} at $V_w(k)$ index. If the entry of v_{DCopt} at $v_{w index}$ is nonzero, PSF control algorithm will be implemented by giving this entry as reference value $v_{DCref}(k + 1)$ for the next iteration. If the value of v_{DCopt} at

$V_{w\,index}$ is zero, algorithm implements TSR control. Average of the optimal TSR vector $\lambda_{opt\text{-}average}$ is considered as system λ_{opt} and reference voltage $v_{DCref}(k + 1)$ is calculated by using K_b as described in flowchart. Implementation of the PSF and TSR control computations by using programmable memory feature allows the system to immediately jump to the optimal operating point, thereby bypassing the time-consuming searching procedure. Once all the entries of v_{DCopt} in lookup table are filled with nonzero values, then implementation of TSR algorithm will be discarded. Application of stored information facilitates the proposed algorithm to improve the dynamic response of the system. Moreover, self learning of system specific characteristics makes this algorithm adaptive in nature.

The adaptability of the algorithm allows the system to extract as much available wind power as possible under turbulent wind conditions.

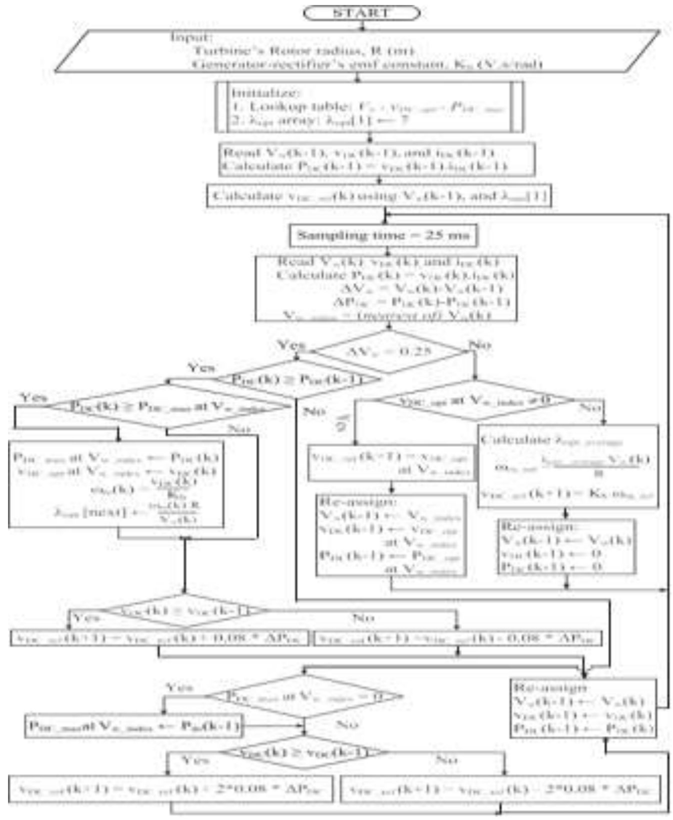


Fig. 3. Adaptive MPPT algorithm flowchart.

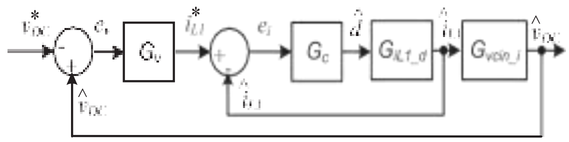


Fig. 4. Double loop current-mode control structure

Fig. 5. Experimental setup

IV.COMPENSATOR DESIGN

A.SEPIC

*Based Plant's Transfer Functions*In this work, dual-loop current mode control, as shown in Fig.4. is implemented for faster dynamic response and to avoid the right half plane zero issue in continuous conduction mode (CCM) operation of the SEPIC converter.

Designed parameters for CCM operation of SEPIC converter are given in Table I. The required transfer functions for the controller design are derived from the small-signal state-space model of the plant given in(11) by applying Laplace transform and are given in (16)–(18).

B.*Digital Controller Design*

Proportional gain along with a dominant pole with zero compensation [27] controllers are tuned for faster inner current loop (phase margin = 75.6° at gain cross-over frequency = 3.28 10^4 rad/s) and relatively slower outer voltage loop (phase margin = 56.3° at gain cross-over frequency=3.0810^4 rad/s) Digital redesign approach [28] is used in this work for the development of the compensators.

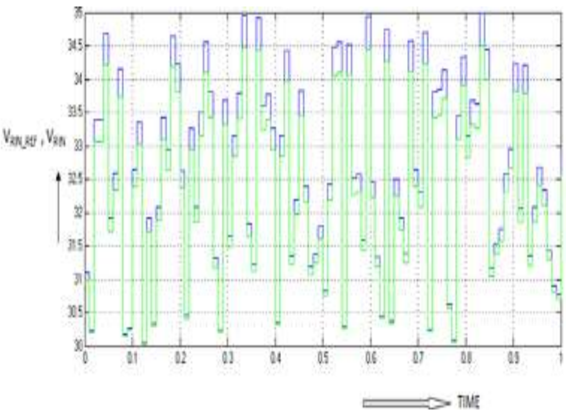


Fig. 6. SEPIC's reference signal tracking respons

V. EXPERIMENTAL RESULTS

An experimental setup shown in Fig. 6, has been developed for the performance evaluation of the proposed MPPT control algorithm in extracting maximum power by a given WECS.

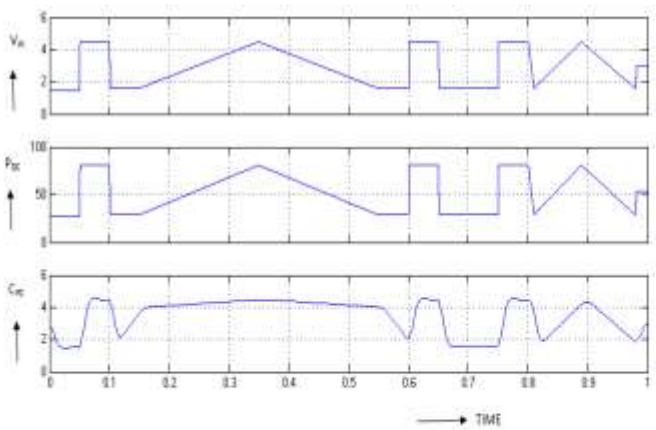
SEPIC dc–dc converter's response in reference signal track- ing with double loop current mode controller has been verified and is shown in Fig.8. The observed performance ensures that the tracking behavior of the converter is satisfactory even at wide variations in reference signal.

Performance Evaluation of Proposed MPPT Algorithm

After running the system with proposed MPPT algorithm for the duration of 5000 s, it is observed that average value of the optimal TSR vector $\lambda_{\text{opt-average}}$ is 7.91 and data stored in lookup table is presented in Table II. In this section, be- havior of the WECS with proposed MPPT algorithm is ana- lyzed by using two stages of evaluations. In first stage, effec- tiveness of the proposed MPPT algorithm is evaluated by ob- serving the system performance in extracting maximum power under sudden and gradually varying wind conditions. In sec- ond stage of evaluation, a comparative study has been done between system performance with conventional HCS algo- rithm and proposed MPPT algorithm against turbulent wind conditions.

1. *System Performance With Proposed MPPT Algorithm:*

Fig.7 shows performance of the WECS with proposed MPPT algorithm under sudden and gradual varying wind conditions. In Fig. 10(a), at time t_1, when system experiences a sudden vari- ation in wind velocity from 4.5 to 6.5 m/s, algorithm executes turbulent wind condition related computations and searches the lookup table for v_{DCopt} at the index wind velocity of 6.5 m/s. Since the data at v_{DCopt} is 86.81, algorithm implements PSF feature and provides reference signal immediately to the con- troller without any random search process. During next sam- pling time, (t_1 + 25 ms), since the wind velocity remains at 6.5 m/s, algorithm implements HCS feature and updates the programmable memory's P_{DCmax} and v_{DCopt} if it observes that (t_1 + 25 ms) > P_{DC} (t_1). At t_2, when wind velocity reduces to 5 m/s, algorithm retrieves optimal characteristics from the lookup table and generates reference signal v_{DCopt} as 82.11 V by im- plementing PSF feature of the algorithm under turbulent wind condition related computations. From t_2 to t_3, performance of the WECS is observed during gradual variations in wind veloc- ity from 4.75 to 7 m/s and then from 7 to 4.75 m/s. Variations in power coefficient between t_1 and t_3 are nearly 4.7 and this ensures the optimal performance of the system throughout the duration under turbulent and gradual wind varying conditions. To ensure the system's optimal performance, similar wind ve- locity conditions are applied to the system from t_3 to t_6, and it can be observed that system operation is always near to MPP .Moreover, proposed algorithm's continuous modifications in programmable memoryduring its implementation, make the optimal tracking performance of the system more ef- fective and efficient.



. Fig.7. Performance of WECS with proposed MPPT algorithm for Dynamic response under varying wind conditions.

2. *Comparative Study of System Performance With HCS Al- gorithm and Proposed MPPT Algorithm:*

System performance with HCS algorithm and proposed MPPT algorithm under fluctuating wind conditions are compared in this section. HCS algorithm provides reference signal by using

$$v_{DC_{ref}}(k+1) = v_{DC_{ref}}(k) + \eta \ (P_{DC}(k) - P_{DC}(k-1)) \qquad (20)$$

where η is incremental step factor. System response with HCS algorithm is shown in Fig. 8(a) and (b). Fig. 9(a) and (b) show the performance of the system with proposed MPPT algorithm.

In Fig.8(a), at instant t_1, when wind velocity changes sud- denly from 5 to 6.5 m/s, HCS algorithm needs four adjustment cycles before reaching to the optimal operating point.

Whereas, proposed algorithm provides reference signal $v_{DCopt}(k+1)$ =86.81 V by using lookup table data and it places the system promptly at MPP without any arbitrary variations as shown in Fig. 9(a)

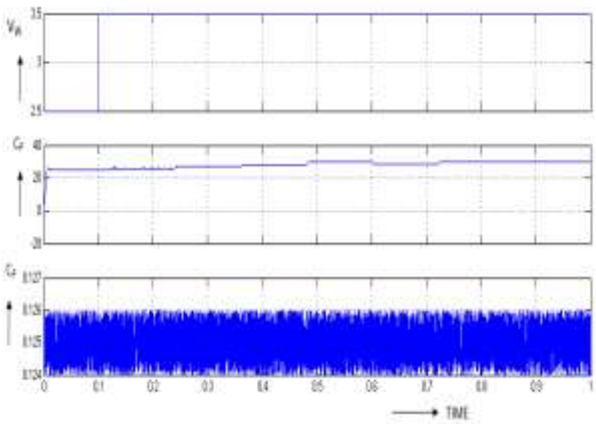


Fig.8.(a) Performance with HCS algorithm

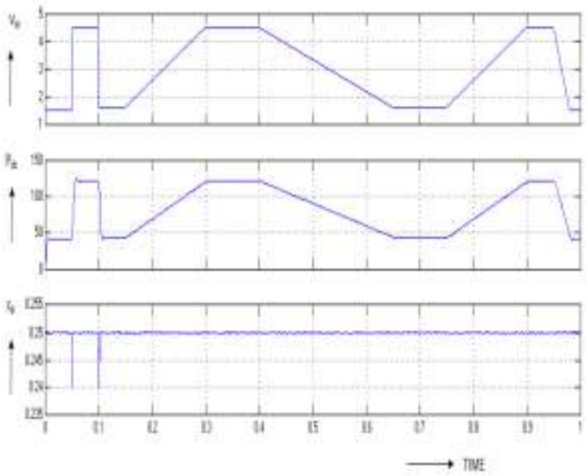


Fig.8.(b) Performance with HCS algorithm

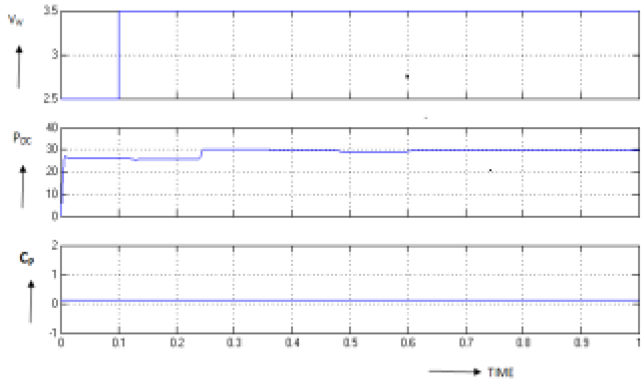


Fig.9.(a).Perfomance with PROPOSED agorithm

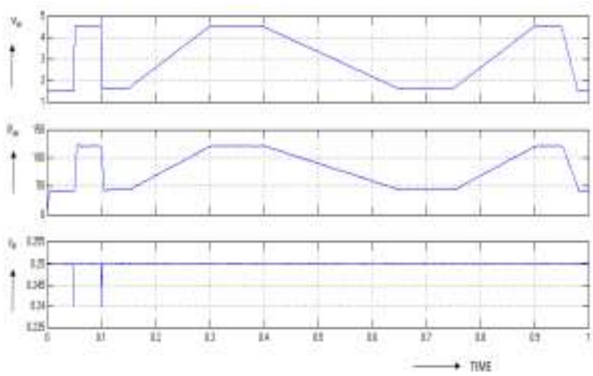


Fig.9.(b) Perfomance with PROPOSED agorithm

CONCLUSION

In this paper, an adaptive MPPT control algorithm has been proposed for the fast tracking of MPP under turbulent windconditions for small-scale WECSs. System behavior with pro posed algorithm under fast changing wind conditions has been observed and it is evident that the proposed control algorithm can put the system at optimal operating point promptly against random variations in the wind velocity. System performance with proposed algorithm is compared with the HCS algorithm and experimental results proved that WECS with proposed al gorithm harvests more energy than with HCS algorithm. The proposed algorithm provides the following advantages: 1) im proved dynamic response of the system; 2) prerequisite of sys tem's optimal characteristics data is not required and hence the algorithm is adaptive; and 3) algorithm's continuous modifica- tions on programmable memory towards optimal characteristics of the system, eliminate the possibility of system's performance degradation due to parameters variations. To extract maximum power from the wide range of wind conditions, SEPIC converter is used for the implementation of proposed MPPT algorithm. Since small-scale WECSs are main resources for DERs in mi- crogrid systems, the proposed algorithm is very much applicable for microgrid systems.

REFERENCES

[1] D. S. Zinger and E. Muljadi, "Annualized wind energy improvement using variable speeds," *IEEE Trans. Ind. Appl.*, vol. 33, no. 6, pp. 1444–1447, Nov./Dec. 1997.

[2] A. Miller, E. Muljadi, and D. Zinger, "A variable speed wind turbine power control," *IEEE Trans. Energy Convers.*, vol. 12, no. 2, pp. 181–186, Jun. 1997.

[3] R. Chedid, F. Mrad, and M. Basma, "Intelligent control of a class of wind energy conversion systems," *IEEE Trans. Energy Convers.*, vol. 14, no. 4, pp. 1597–1604, Dec. 1999.

[4] H. Li, K. Shi, and P. McLaren, "Neural-network-based sensorless max- imum wind energy capture with compensated power coefficient," *IEEE Trans. Ind. Appl.*, vol. 41, no. 6, pp. 1548–1556, Nov./Dec. 2005.

[5] A. S. Satpathy, N. Kishore, D. Kastha, and N. Sahoo, "Control scheme for a stand-alone wind energy conversion system," IEEE Trans. Energy Convers., vol. 29, no. 2, pp. 418–425, Jun. 2014.

[6] S. Morimoto, H. Nakayama, M. Sanada, and Y. Takeda, "Sensorless output maximization control for variable-speed wind generation system using ipmsg," in Proc. IEEE 38th Ind. Appl. Annu. Meeting Conf. Rec., 2003, vol. 3, pp. 1464–1471.

[7] R. M. Hilloowala and A. M. Sharaf, "A rule-based fuzzy logic controller for a pwm inverter in a stand alone wind energy conversion scheme," in Proc. IEEE Ind. Appl. Soc. Annu. Meeting Conf. Rec., 1993, pp. 2066– 2073.

[8] V. Galdi, A. Piccolo, and P. Siano, "Designing an adaptive fuzzy controller for maximum wind energy extraction," IEEE Trans. Energy Convers., vol. 23, no. 2, pp. 559–569, Jun. 2008.

[9] A. Raju, B. Fernandes, and K. Chatterjee, "A upf power conditioner with maximum power point tracker for grid connected variable speed wind energy conversion system," in Proc. IEEE 1st Int. Conf. Power Electron. Syst. Appl., 2004, pp. 107–112.

[10] M. Chinchilla, S. Arnaltes, and J. C. Burgos, "Control of permanent- magnet generators applied to variable-speed wind-