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Extremum Seeking Control Scheme for WECS Using Matrix Converter

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Abstract:

Renewable energy applications have brought a new focus on the capabilities of ES algorithms. In this article we present applications of ES in two types of energy conversion systems for renewable energy sources: wind and solar energy. The goal for both is maximum power point tracking (MPPT), or, the extraction of the maximum feasible energy from the system under uncertainty and in the absence of a priori modeling knowledge about the systems. For the wind energy conversion system (WECS), MPPT is performed by tuning the set point for the turbine speed using scalar ES. The outer ES loop tunes the turbine speed to maximize power capture for all wind speeds within the subrated power operating conditions. The inner-loop nonlinear control maintains fast transient response through a matrix converter, by regulating the electrical frequency and voltage amplitude of the stator of the (squirrel-cage) induction generator. Simulation results are presented to show the effectiveness of the proposed design.

Index Terms:

Adaptive systems, nonlinear control systems, power control, wind power generation.

I.INTRODUCTION:

Wind energy is presently the fastest growing among all renewable energy systems. Among the WECSs, variable speed ones in recent years have become the industry standard because of their advantages over fixed speed ones such as improved energy capture, better power quality, reduced mechanical stress and aerodynamic noise [1]. Further, variable speed WECS can be controlled over a wide range of wind speeds to enable the WECS to operate at its maximum power coefficient thus, allowing it to obtain a larger energy capture from the wind [2]. However, conventional variable speeds WECS with speed-up gears due to its many disadvantages have given way to direct drive (DD) WECS. The DD WECS, compared to WECS with speed-up gears, have reduced overall size, lower maintenance cost in addition to having higher overall efficiency and reliability [3], [4]. In developing new DD WECS designs, PMSG is favoured more and more over electrically excited synchronous generators because of higher efficiency, higher power densities, availability of high-energy permanent magnet material at reasonable price, and possibility of smaller turbine diameter [4]. Maximum power extraction from WECS has been the subject of several recent research investigations. In order to extract maximum possible power from the available wind power, it is necessary to drive the WECS at its optimum speed of rotation using a MPE controller.

The MPE control, in conventional wind energy conversion systems, is implemented using wind speed data obtained from wind speed sensors [5]-[7]. However, use of wind speed sensors raises the problem of calibration and measurement accuracy, as well as increases the initial cost of wind generation systems. Therefore, wind speed sensorless MPE control is a very active research area [8]. Tip speed ratio (TSR) control methods using estimated wind speed are presented in [9]. Estimation of wind speed requires heavy computation which however is the main disadvantage of these methods. In [7], hill climb search (HCS) control methods are presented. The HCS control methods work well with small inertia wind turbines but not very effective for large inertia ones. In [5], optimum torque (OT) control methods are presented. In these methods, the controller adjusts the generator torque to optimum values at different wind speeds using a look-up table.

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Using speed as the input, the methods in [6] generate optimum reference torque for the control of machine side converter. The OT control methods, due to system inertia, are slow in response. Therefore, a sudden change in wind speed does not cause a sudden change in rotor speed. Optimum turbine power curve has been used successfully by many researchers in order to develop wind speed sensorless MPE controllers. In these methods, known as power signal feedback (PSF) control, using rotor speed as input, the controller generates optimum power at its output which is then tracked, using appropriate controllers, to produce maximum power. PSF control is used in [4], to extract maximum power. PSF along with feedback linearization control are used in order to realize MPE control in [5]. In [6], addition of proportional controller in PSF controller is proposed to reduce the effect of turbine inertia and improve speed of response of the controller.

The methods presented in [7] require the knowledge of optimum power curve of their respective turbines which are tracked through their control mechanisms. They use rotor speed as the input and generate optimum power as the output. The drawback of these methods is that the optimum power curves, which they rely on, are generated using their respective optimum power constants which actually are not constants but vary with the change in operating points of the WECS due to the change in wind speed. Moreover, these methods, similar to OT control method, are slow in response. Further, these methods don’t take air density which changes considerably from season to season into account, thus, resulting in low tracking accuracy of these controllers.

II.WIND ENERGY CONVERSION SYSTEM:

Machine Side Converter Control System:

The dynamic model of surface mounted PMSG in rotor flux reference frame is given by

Vsd = -Rsisd - Ls disd/dt = wLsisq

Where Vsd and Vsq are the d and q components respectively of stator voltage, isd and isq are the d and q components respectively of stator current, ω is the generator speed, ψ r is the rotor flux, Rs is the stator resistance and Ls is the stator inductance. The electromagnetic torque is given by

T = (3/2) T / pi ψrisq

For control of the PMSG, a vector control approach is used where control is exercised on the rotor flux reference frame. The block schematic of the machine side converter control system is shown in Fig. 1. The required d-q components of the stator voltage vector are derived from two PI controllers: one of them controls the d-axis component of the current and the other, q-axis component.For fast dynamic control capability compensation terms Vcq and Vcd are added to the direct and quadrature axis current regulator outputs respectively to form command d and q voltage.The proposed MPE controller generates * ω , the reference speed which when set as the command speed for the speed control loop of the machine side converter control system, maximum power points will be tracked by the WECS. The details of the MPE controller will be discussed in the next section.

Maximum Power Extraction Controller:

The torque developed by a wind turbine is given by

$$T_m = 0.5\pi\rho C_p(\lambda,\beta)R^3 v_w^2 / \lambda$$

Where ρ is the air density, Cp is the power coefficient, λ is the tip speed ratio, β is the pitch angle, R is the turbine radius, and Vw is the wind speed. The TSR is given by λ = ωr/R Vw Where ωr is the turbine angular speed. The wind turbine power is given by

$$P_m = 0.5\pi\rho C_p(\lambda,\beta)R^2 v_w^3$$

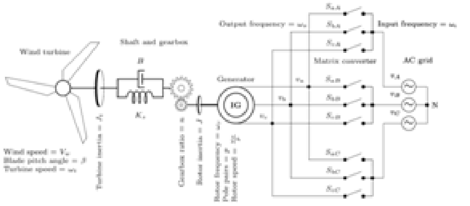

Fig 1: WECS including WT, gear box, IG, and MC

As shown in Fig. 1, the generator is connected to the ac grid through an MC, which includes nine bidirectional switches operating in 27 different combinations. MCs provide bidirectional power flow, sinusoidal input/output currents, and controllable input power factor. Due to the absence of components with significant wearout characteristics (such as electrolytic capacitors), MC can potentially be very robust and reliable. The amount of space saved by an MC, when compared with a conventional back-to-back converter, has been estimated as a factor of three. Therefore, due to its small size, in some applications, the MC can be embedded in the machine.

III.MATRIX CONVERTER:

The matrix converter has several advantages over traditional rectifier-inverter type power frequency converters. It provides sinusoidal input and output waveforms, with minimal higher order harmonics and no subharmonics; it has inherent bi-directional energy flow capability; the input power factor can be fully controlled. Last but not least, it has minimal energy storage requirements, which allows to get rid of bulky and lifetime-limited energy-storing capacitors.But the matrix converter has also some disadvantages. First of all it has a maximum input output voltage transfer ratio limited to @ 87 % for sinusoidal input and output waveforms. It requires more semiconductor devices than a conventional AC-AC indirect power frequency converter, since no monolithic bi-directional switches exist and consequently discrete unidirectional devices, variously arranged, have to be used for each bi-directional switch. Finally, it is particularly sensitive to the disturbances of the input voltage system.

The matrix converter consists of 9 bi-directional switches that allow any output phase to be connected to any input phase. The circuit scheme is shown in Fig.2. The input terminals of the converter are connected to a three phase voltage-fed system, usually the grid, while the output terminal are connected to a three phase current-fed system, like an induction motor might be. The capacitive filter on the voltage-fed side and the inductive filter on the current-fed side represented in the scheme of Fig.2 are intrinsically necessary. Their size is inversely proportional to the matrix converter switching frequency.

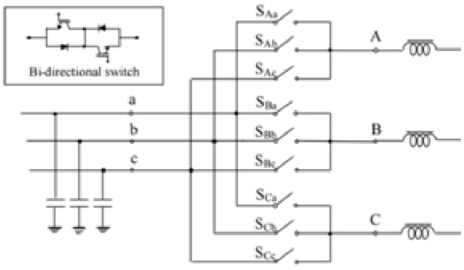

Fig 2: Three phase to three phase matrix converter.

IV.CONTROL SYSTEM:

In many motor drive systems, it is desirable to make thedrive act as a torque transducer wherein the electromagnetictorque can nearly instantaneously be made equal to a torquecommand. In such a system, speed or position control isdramatically simplified because the electrical dynamics of thedrive become irrelevant to the speed or position control problem. In the case of induction machine drives, such performancecan be achieved using a class of algorithms collectively knownas FOC. When flux amplitude, sqrt ($\lambda 2\alpha + \lambda 2\beta$), is regulated to a constantreference value, and considering the fact that the dynamicsof ωt are considerably slower than the electrical dynamics,we can assume that the dynamics are linear, but during fluxtransient, the system has nonlinear terms and it is coupled.

This method can be improved by achieving exact input–outputdecoupling and linearization via a nonlinear state feedback thatis not more complex than the conventional FOC. There are three main MPPT techniques for WECS: windspeed measurement (WSM), P&O, and PSF. Measurement ofwind velocity is required in WSM method. It is clear thataccurate measurement of wind velocity is complicated andincreases the system cost.

Since the P&O method adds delay,it is not practical for medium- and large-inertia WT systems.To implement PSF control, maximum power curve (maximumpower versus turbine speed) is required. The maximum poweris then tracked by turbine speed control.Fig. 3 shows a typical block diagram of P&O using direct FOC for the IG. To implement FOC scheme, the rotorflux magnitude $|\lambda|$ and its angle ϕ are identified by the rotorflux calculator based on the measured stator voltage (vo) andcurrent (io).

The turbine speed reference ωrefe is generated bythe MPPT scheme.To overcome challenges attached with the conventionalpower control and optimization algorithms and to remove thedependence of the MPPT algorithm on the system modelingand identification, we propose ES algorithm, which is anonmodel-based real-time optimization technique to MPPT ofWECS. First, we present ES without the inner-loop controlto clarify the advantages of the proposed controller on theclosed-loop performance of the system.

In this paper,we assume that we have access to turbine power measurementsand we can manipulate the turbine speed through the MC.Furthermore, we do not have a model of the power coefficientor turbine power. The following holds for the turbine powermap around its MPP for $Vcut-in<Vw<Vrated$

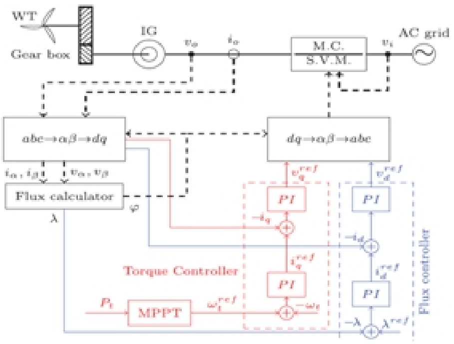

Fig 3: MPPT for a WECS based on P&O using conventional direct FOC

A schematic diagram of MPPT for WECS with ES withoutinner-loop nonlinear control is shown in Fig. 4. Remark 4implies that the power is parameterized by ωo, which is estimatedby ES loop. The other input for WECS that generatesthe voltage amplitude has been set to zero, which means thestator voltage has constant peak amplitude.

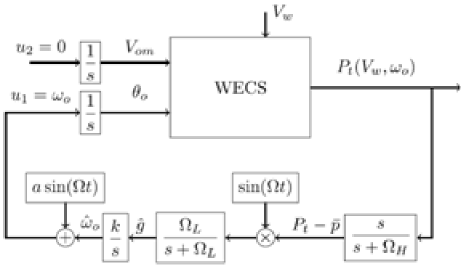

Fig 4: MPPT for a WECS based on ES without the inner-loop control.

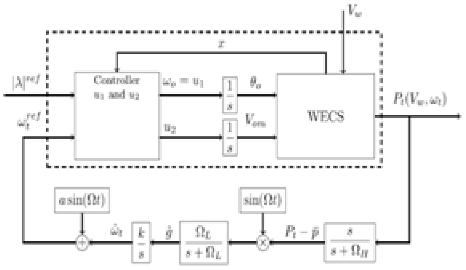

Fig 5: ES for MPPT in WECS with the inner-loop control.

The turbine power measurement is fed into ES scheme. Theoptimization parameter for ES without the inner-loop control,Fig. 5, is the electrical frequency of IG stator, ωo. Stability ofsystem dynamics is required for convergence of ES algorithmto its peak point. It is also required that the ES algorithm worksmore slowly than the WECS system dynamics. As previously mentioned, since WECS in Fig. 4 without the inner-loopcontroller shows a slow transient, the entire system has alengthy convergence process, which results in low powerefficiency.

V.SIMULATION RESULTS:

Response time of the ES designwithout the inner loop is considerably slow, which resultsin a very low power efficiency. However, we present onesimulation that compares the response of the design withoutthe inner loop, as shown in Fig. 4, to our proposed algorithm,as shown in Fig. 5, which shows the role of the inner loop.

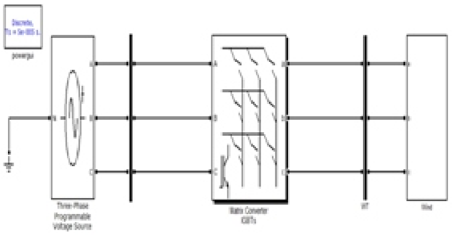

Fig 6: Wind Energy Conversion System

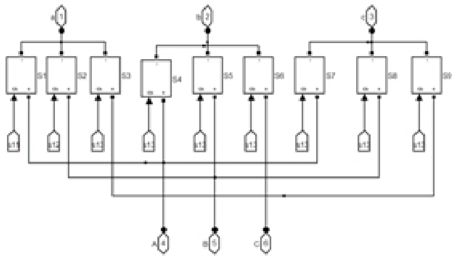

Fig 7: Matrix Converter

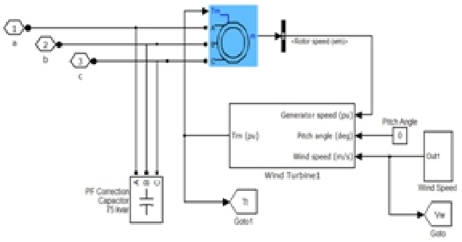

Fig 8: wind turbine, Induction generator

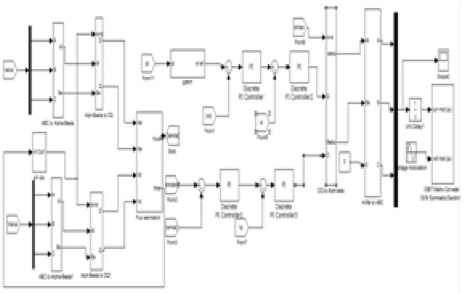

Fig 9: control strategy

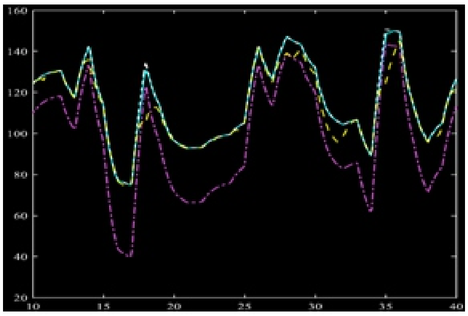

Fig 10: MPPT, (blue) our proposed algorithm, (pink) ES without inner loop, (yellow) conventional P&O with FOC,and (white line) maximum power available to the WECS.

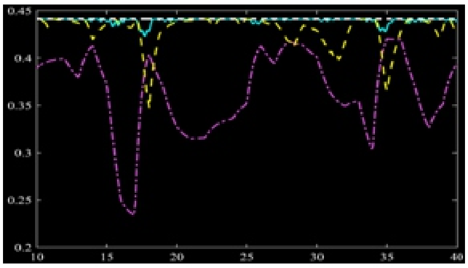

Fig 11: Variation of power coefficient, (blue) our proposedalgorithm, (pink) ES without inner loop, (yellow) conventional P&O with FOC, and (white) maximum powercoefficient.

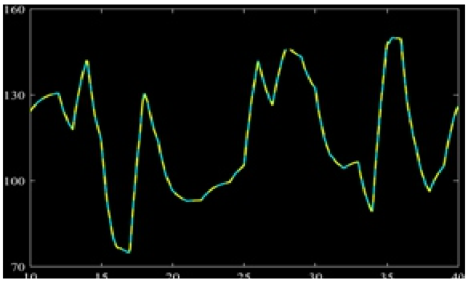

Fig12: Robustness analysis with a 100% increment in the rotor resistorat time 15 s and back to its nominal value at time 25 s for the proposedalgorithm. Variation of turbine power (blue) with perturbation and(yellow) without perturbation

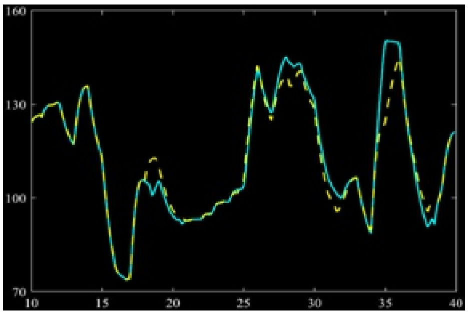

Fig13: Robustness analysis with a 100% increment in the rotor resistor attime 15 s and back to its nominal value at time 25 s for conventional P&Owith FOC. Variation of turbine power (blue) with perturbation and(yellow) without perturbation

Our algorithm provides perfect input–outputdecoupling and guarantees a larger domain of attraction, whichincreases performance robustness with respect to the systemparameters. However, one may question the implementationcomplexity of the proposed algorithm.Clearly higher powerefficiency is our aim and to this end, we have to sacrificethe simplicity in favor of harvesting more energy. Since theWECS runs for a long period of time, a small improvement inpower efficiency guarantees extracting a higher energy leveland leads to cost reduction of the WECS.

VI.CONCLUSION:

The design employed an inner-loop nonlinearcontroller based on field-oriented approach and feedbacklinearization technique to control the closed-loop transientperformance, with respect to which the ES had to be tuned. Without this inner-loop control, the convergence rate of theclosed-loop system would be much slower. This optimization/control algorithm can readily be extended to other classesof WECS without major changes.The main parameters thatneed to be adjusted are the probing frequency and amplitudeof the perturbation signal. Furthermore, the proposed controlstrategy prevents magnetic saturation in the IG.

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