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Gain Scheduling Proportional Integral for Standalone Wind Energy System

Siddharth Joshi*, Vivek Pandya and Bhinal Mehta

Department of Electrical Engineering, Pandit Deendayal Petroleum University, Gandhinagar – 382007, Gujarat, India; drsiddharthjoshi85@gmail.com

Abstract

The isolated location in developing countries like India where grid is not readily accessible, the standalone system with renewable or with conventional source is inevitable. Due to the ample availability of solar and wind energy, they are the most suitable and affordable energy sources in the standalone mode. The fixed gain proportional integral controller is usually obtained in such system. These controllers are tuned for specific conditions to obtain the voltage regulation, so optimal tuning of these controller is necessary to acquire desired operation of the overall system. This can be done by scheduling the gain dynamically. This paper focuses on the incorporation of gain scheduling proportional integral controller applied to the standalone wind energy conversion system with change in wind speed conditions. The real data for the wind speeds are taken for the location of Ahmedabad, Gujarat, India to check the performance of wind energy system connected with DC load and analysis is done at average wind speed.

Keywords: Gain Scheduled PI Controller, Standalone System, Wind Energy Systems

1. Introduction

There is an inevitable growing attention in the area of renewable technology sector due to the rising energy demands in all the fields with increases in population, human development index, global warming, and unstable fossil fuel economy. Table 1 shows that installed capacity of different types of power sources in India from 2011-18[1]. The contribution of renewable energy particularly wind and solar in meeting the energy demand from 2011-18 is gradually increasing. Looking at the growth development of India, the consumption of the fuel is increasing and the power demand is also increasing day by day and renewable technologies is playing a major role to bridge the demand supply gap. Present status of India, power shared by renewable is about 20% in comparison with conventional plants in 2018[1]. A stand-alone energy system with incorporation of renewable energy sources, have not only the advantages of the reduction carbon foot prints and to serve the purpose of rural electrification (power to all) but also reduces the distribution and transmission cost. The standalone system may be defined as grid powered by a combination of different energy sources for feeding the domestic/commercial loads over a small area.

Table 1. Generation in MW of the sources over the years (2010 TO 2018) in India[1]

Type of Sources	2011	2012	2013	2014	2015	2016	2017	2018
Solar	35.15	941.24	1686.44	2631.96	4878.88	9012.69	12289	24021
Wind	14156	17353	19051.46	21136.4	25088.19	28700.44	32300	34615
Biomass	2665	3135	3601.03	4013.55	4450.55	4856.94	5108	8730
Small Hydro Power	3043	3395	3632.25	3803.7	4176.83	4333.86	4486	4506
Thermal	111380	131282	151101	168361	188898	189047.9	218330	223027
Hydro	37567	38990	39491	40531	41267	44413	44478	45400
Nuclear	4780	4780	4780	4780	5780	5780	6780	6780

*Author for correspondence

2. Wind Turbine Modelling

The mechanical power from available wind is[2],

$$P_{mech} = \frac{1}{2}\rho A v^3 \tag{1}$$

Power captured by the blades of a wind turbine is,

$$P_{net} = P_{mech} \times C_P \tag{2}$$

where, P_{mech} = Mechanical power from wind turbine in Watt. P_{net} = Net power from wind turbine after Betz limit and multiplication of power coefficient, r = Air density (1.225kg/m^3), A = Swept area of wind turbine in m^2, v = Velocity of wind or wind speed in m/s.

C_p is a power coefficient and it is a function of Tip Speed Ratio (TSR) (l) and blade pitch angle (b) TSR can be defined as ratio of wind speed at the tip of the blade divided by the wind speed[2].

$$TSR = \frac{\omega R}{v} \tag{3}$$

where, R is the radius of wind turbine and w is the angular speed of wind turbine. In practice, as per Betz limit[3,4] C_p cannot be exceeded from their theoretical limit i.e. 0.59. For low-speed wind machines, C_p ranges from 0.2 to 0.4 and for large wind machines up to 0.5 is observed. Graph between TSR and power coefficient is discussed in [3,4].

3. MPPT Algorithm for Standalone Wind Energy Conversion System

Maximum Power Point Tracking (MPPT) technique is well known for solar technologies. Similar to Photovoltaic (PV) applications, various MPPT algorithm can also be used in the wind energy application in standalone mode as well as grid tied mode. Broadly, the MPPT algorithms for Wind Energy Conversion System (WECS) are categorized into three types: Tip-Speed Ratio Control (TSR), Power-Signal Feedback (PSF), Hill Climb Search (HCS) based [5-6]. TSR control method regulates the wind rotor speed to maintain an optimal TSR and it requires the prior knowledge of wind speed and speed of turbine at that wind speed. Since TSR is a ratio of the speed of the tip of blade to wind speed, it depends upon both the speeds. This scheme encounters disadvantage of significant error in measurement of wind speed particularly in large wind farm and its shadow effects.

For Optimum Relationship Based (ORB) control the maximum power point is tracked with optimum relation between various system variable. In this algorithm the response is fast in case of change in wind speed[5–7]. Such algorithms have good dynamic response and ease of implementation. The main disadvantage of this scheme is one can need prior knowledge of the system to run the tracking system in effective manner. PSF control requires the knowledge of the wind turbines maximum power curve obtained for a turbine via simulations or testing of the turbine by taking some reference speed. It makes the system complicated and difficult to operate.

Another popular method is Perturb and Observe (P&O) control, which is also known as HCS control used in[5]. The turbine speed is adjusted toward the maximum power point by regulating the DC side voltage or current. Once the optimum relation is defined for a system, it can be used by P&O control algorithms to track the maximum power point by continuously changing the maximizing variable and observing the power captured. Based on the power measurements the variation with the perturbation introduced, the next perturbation size and direction may be determined until the algorithm reaches the maximum power point. Most of the work done for MPPT using P&O has used the power-speed relation of the wind turbine 3–4.

The MPPT algorithm proposed in[5] is used in this work for WECS. This is an adaptive part of conventional P & O method using constants in the algorithm. The algorithm initializes the system variables and the samples from the DC voltage and current are taken. The DC link voltage will change with change in wind speed. Multiplying with the inductor current will give a new value of DC power. This value is used in calculation inside the algorithm. The algorithm is designed to monitor the change in slope with variation in DC link voltage. So, one can identify from the change in slope that, whether it is steady change in wind speed or it may be sudden change in wind speed.

Three constants are introduced K_0, K_1 and K_2 for the slope and from that reference value of DC current is generated at that wind speed. There is also a feature of detection of change in wind speed by observing the change in DC link voltage in the proposed in algorithm used in[5,6]. The power co-efficient (Cp) based MPPT method for WECS is proposed in[7,8]. The wind energy based standalone system with other sources are proposed in[14-17].

4. System Description and Gain Scheduling Pi Controller

The test system comprises of 3 kW permanent magnet synchronous generator (PMSG) connected with 4 kW wind turbine, which is variable speed turbine. With the developments in power electronics variable speed wind turbine draws more attention globally and the advantages of PMSG over other generator is proven in several literatures[7,8,13]. The output of the generator is given to the uncontrolled DC-DC boost converter, which is further connected with DC load with MPPT algorithm.

The block diagram for WECS having Gain Scheduling Proportional Integral (GSPI) controller is shown in Figure 1.

The MPPT controller is working in closed loop manner.

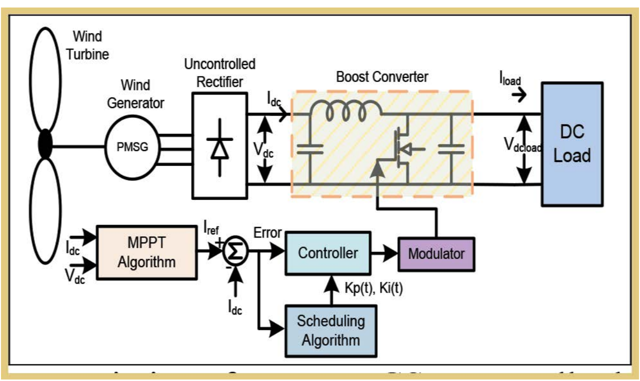

Figure 1. Description of system – GSPI controller based WECS.

Conventionally Proportional Integral (PI) controller incorporated with the MPPT algorithm regulates the reference value of the current or voltage to generate the variable pulse for boost converter. The duty cycle can be varying with change in atmospheric condition such as wind speed in this case. The hybrid system comprises of PMSG based wind energy conversion system with fuel cell and electrolyser as proposed in [9], they used proportional integral controller to demonstrate the results.

The fixed gain controller has the disadvantages like higher probability of failure at high level of vagueness, failure to operate in desired manner under the change in input conditions, need to re-tune gains. Zeigler Nicolas method can help in the determination of controller gains, but it is an offline tuning method. Moreover, this method has some limitations of little usage of process information in design criterion leading poor robustness. On the other hand, gain scheduling can be an alternative due to its ability to track the rapid changes in the operating conditions in this case it is wind speed. Therefore, to solve the problems of conventionally PI controller marginally (not changing in system parameters) the GSPI algorithm / controller is used in the proposed system for wind energy conversion system.

The GSPI controller is used in place of conventional PI controller as shown in Figure 1. The effectiveness of algorithm is observed at load end voltage. This controller implements the control algorithm for PI controller with the change that instead of constant gains, the proportional and integral gains are varied depending on the error input.

The operation of the GSPI controller is divided in to two stages: Stage 1: Determination of PI controller gains with respect to the error input; Stage 2: Determination of the PI controller output with the controller gains decided in Stage 1. Figure 2 shows the block diagram for GSPI controller implemented for the control of primary and auxiliary source. The output of GSPI, udc(t), can be mathematically defined as [10];

$$u_{dc}(t) = k_p(t) * e(t) + k_i(t) \int e(t)dt \tag{4}$$

where, e(t) is the sensed or actual value of voltage/ current, $k_p(t)$ and $k_i(t)$ are the instantaneous values of proportional and integral gains, and t is time. $k_p(t)$ can be represented as a function of the input error signal e(t) as in (5), where 'a' is a constant, k_{pmax} and k_{pmin} are the maximum and the minimum values of k_p. When e(t) is large, the exponential term approaches zero, therefore $k_p(t) = k_{pmax}$. Similarly, when e(t) is small, the exponential term approaches unity. This results in $k_p(t) = k_{pmin}$. This implies that larger the e(t), larger will be the k_p resulting in fast response during transient period. To avoid the undesirable problems of overshoot, the gain scheduling algorithm ensures that $k_p(t)$ is small when e(t) is small. Hence, $k_p(t) = k_{pmin}$. The constant 'a' in (5) determines the rate of variation of the proportional gain. For the transient conditions, the large proportional gain is employed to drive the large error towards zero and thereby, drive the process towards the steady state condition[10].

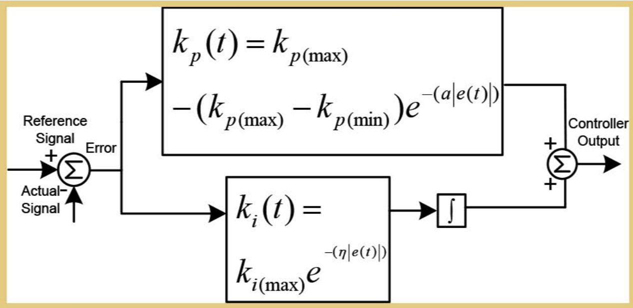

Figure 2. Gain scheduling PI controller structure.

$$k_p(t) = k_{p(\max)} - (k_{p(\max)} - k_{p(\min)})e^{-(a|e(t)|)} \tag{5}$$

Integral gain, $k_i(t)$, in (4) as a function of error signal e (t) can be expressed as[11,12],

$$k_i(t) = k_{i(\max)}e^{-(\eta|e(t)|)} \tag{6}$$

where; h is a constant, $k_{i\,(\max)}$ are the maximum value of integral gain. The value of h varies between 0 to 1 depending upon e(t). If e(t) is small, $k_i(t)$ needs to large so as to drive the steady state error to zero. Conversely, if e(t) is large, then the system in transient state and the significance of $k_i(t)$ is small[10–12]. In this work 'a' is taken as a unity and 'h' is taken as 0.1. From the above equations the generalized behaviour of GSPI controller is as shown in Figures 3 and 4. These figures provides the behaviour of Gain Scheduling Proportional Integral Controller (GSPIC) response in terms of k_p and k_i with respect to change in error.

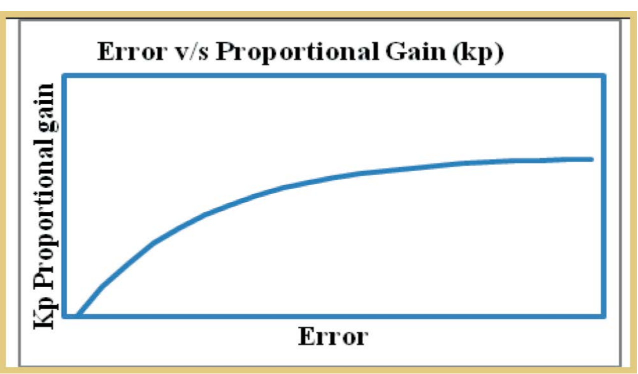

Figure 3. Generalized graph for the error v/s proportional gain.

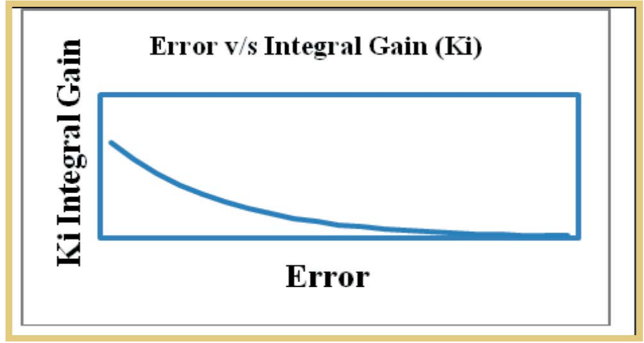

Figure 4. Generalized graph between error and integral gain.

5. Results and Analysis of WECS with GSPIC

The proposed system is simulated in PSIM® 9.3.4 software. The WECS of 3 kW is taken for the simulation. The MPPT block with algorithm is used for this work. The main aim of the GSPIC is to operate WECS at its MPP with change in wind speed and determination of MPP. At the first stage the gain of GSPIC is obtained with respect to error input and in second stage determination of the PI controller output with the controller gains decided in Stage 1. The simulations have performed considering following two cases in order to check the effectiveness of MPPT and GSPIC algorithms:

Case (i) Effect on the output voltage with change in proportional gain (k_p) for constant DC load

Case (ii) Results with change in load and change in wind speed.

The Case (i) is performed for constant wind speed of 5.8 m/s. The load resistance is taken as a 27 Ω. The output voltage is observed across load with various values of proportional gain within specific range. The proposed algorithm ensures the maximum power point by generating the current reference from the algorithm. This reference current is compared with the actual current fed to the boost converter. The error signal is given to the GSPIC block for suitable gating pulse. The possible values of k_p and k_i are changed by keeping constant values of k_i and load. The change in output voltage across DC load is observed. The obtained results are as shown in Figures 5–7. The variation of current, power and voltage across the load for WECS are plotted for wind speed 5.8 m/s at 10 m height (considering practical case). Fig. 5 analyses the values of output of GSPIC, value of k_i and value of k_p

at constant wind speed and constant DC load. There is significant impact on output voltage with change in gains of PI which is observed in Table 2. The system simulated with various permutations and combinations of k_p and k_i shows variations in output voltage.

Table 2. Variation in output voltage with change in k_p & k_i

Sr. No.	k_p	k_i	V_{dc} across load in V
1	0.4	0.2	336
2	0.5	0.2	334
3	1.2	0.2	254
4	0.8	0.2	336
5	0.6	0.2	242
6	0.3	0.2	246
7	0.35	0.2	278
8	0.09	0.2	284
9	0.2	0.2	584
10	0.3	0.2	286
11	0.35	0.2	514
12	0.4	0.2	471
13	0.45	0.2	265
14	0.09	0.3	282
15	0.09	1.2	266
16	0.09	2.5	201
17	0.09	2	224
18	0.09	1.8	236

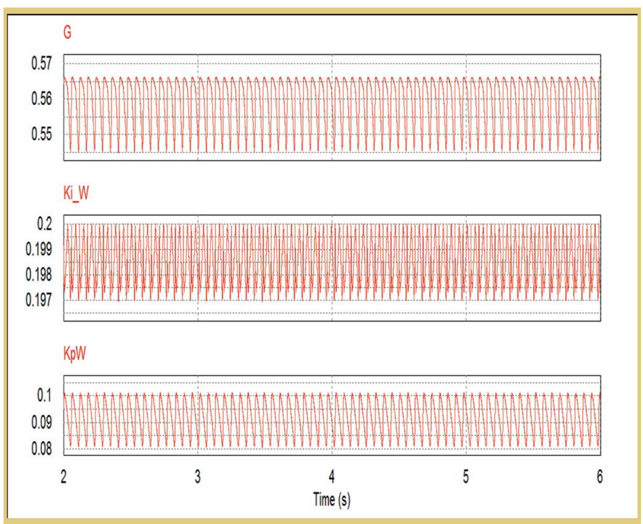

Figure 5. Response of GSPIC with constant load at 5.8 m/s wind speed G=output from the controller, Ki_W=Value of Ki, Kp_W=Value of Kp.

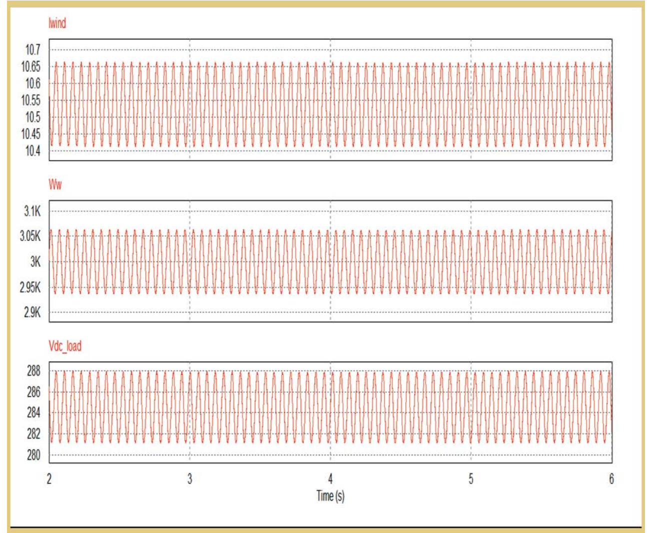

Figure 6. Response of GSPIC with constant load at 5.8 m/s wind speed Iwind = current, Ww=power drawn from WECS, Vdc_load= voltage across load.

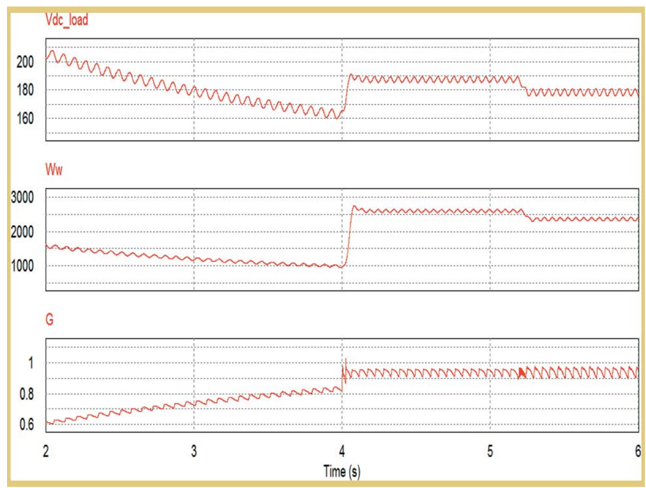

Figure 7. Change in wind speed from 6 m/s to 8 m/s vdc_load=voltage across load, Ww=power drawn, G=output from the controller.

For Case (ii), the response of GSPIC is accountable after the permutation applied in wind speed observed from Figure 6 (named as G - output from the controller). The output response with change in wind speed and change in load is as with GSPIC is shown in Figure 7. The magnitude of the wind speed is changed after 4 seconds from 6 m/s to 8 m/s. The change in DC power consumed by the load is observed from the Figure 7 and also variation in voltage across load.

Similarly, the reflection of output from the controller is shown in Table 2 in terms of change in voltage across DC load with change in maximum value of proportional gain k_p. The significant change is observed by varying k_{pmax} or kp largely, however the significant change in k_i responses the behaviour of controller as it is the response with integral term.

6. Conclusion

This paper reports GSPIC and is applied to the WECS for standalone DC load with MPPT algorithm. The gains of GSPIC are varied within the set limits during the steady state and the transient condition. The obtained controller outputs for WECS drives the DC-DC converter connected with WECS. The variation of gains is to ensure voltage regulation and operation at MPP. The reference current is generated from the MPPT algorithm for the further generation of gate signal with change in the wind speed. This can be effective solution when grid is not available.

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