Optimization of PID Controller for a Hybrid Power System using Particle Swarm Optimization Technique

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Abstract
With the advancement of technology, power demand is increasing day-by-day. Energy deficiency problem and increasing petroleum/diesel cost has resulted in severe impacts to many technical facts. Introduction of non-conventional energy sources such as wind and photovoltaic energy, which is clean and copiously present in nature, can be possible solutions to these problems. This paper presents optimization of a hybrid power system, with one of swarm intelligent algorithms named as particle swarm optimization (PSO). The hybrid system utilizes PID controllers for controlling its yield. It has been done by studying different combinations of diesel engine generator, wind turbine generator, aqua electrolyzer, fuel cell and battery. With the optimized system parameters, high quality power supply can be delivered to the load and the frequency fluctuations can also be minimized.

Keywords: Hybrid power systems, particle swarm optimization, wind turbine generator (WTG), aqua electrolyzer (AE), fuel cell (FC), diesel engine generators (DEG).

INTRODUCTION
The present era is expected to experience immense growth and challenges for power generation, supply and utilization. Now-a-days the role of renewable energysources is increasing in an exponential rate. It is due to the reason that global awareness for the need of environment protection and requirement of reduction in dependency on fossil fuels in the field of power generation. Thus, exploration of many of the nonconventional sources and their integration to conventional sources are done to provide clean energy and supply the load demand in the most intelligent way [1, 2].

“Hybrid Power Systems (HPS) are small set of co-operating units, generating electricity or electricity and heat, with diversified primary energy carriers (renewable and non-renewable), while the co-ordination of their operation takes place by utilization of advanced power electronics systems” [3]. Hybrid power systems by definition have been developed for the production and utilization of electrical power. HPS are independent of central and large electricity grid and integrate numerous different kinds of sources of power. Generally, HPS can work in connection with power grid or they can work alone as standalone system to provide power to different loads, from one to several homes or farms, small industrial plants up to large local customers. When connected to grid, HPS offer electrical power generated by various sources and feed the excess power back in the grid, in case of more power generation than load demand. Main purpose of hybrid power systems is to deliver power to isolated, remote loads where the price of the connection from long distance transmission or distribution grid is very high. Optimization plays an important role for improving systems performance and
effective working. An optimization algorithm is a method of obtaining the optimum solution of a problem that can be achieved by following a technique and comparing numerous solutions iteratively. To find the best solution for large scale optimization problem, evolutionary algorithms are established. Evolutionary algorithms are population-based metaheuristical algorithms they are inspired by natural biological evolution or social behavior of living beings. Particle swarm optimization is one of these algorithms. It has the upsides of simple usage, stable convergence characteristics, and good computational effectiveness [4].

Therefore, a hybrid power system is proposed in this paper with PID controllers optimized by particle swarm optimization technique. The proposed system can also be used in isolated small islands as a stand-alone system, to reduce fuel consumption of conventionally used in diesel/petrol generation systems and it is also good for global environment protection concerns.

PROPOSED HYBRID POWER SYSTEM
This segment depicts the basics of proposed hybrid power system. The generation subsystems comprise wind turbine generator, diesel engine generator, aqua electrolyzer and fuel cell. Aqua electrolyzer is utilized to change over the fluctuating intensity of wind turbine generator into hydrogen and give it as a fuel to fuel cell [5]. In this way power loss due to wind fluctuation can be minimized and system can be fully utilized.

For controlling the output of each subsystem, PID controller is used and for optimizing the controller performance particle swarm optimization (PSO) is used. The feedback gain parameters \( k_r, k_{fc}, k_{deg} \) are also optimized using PSO to reduce the frequency and power deviations. A series of simulation has been carried out to prove its working for different combination of generation components. Different cases are considered for simulation as shown in Table 1. For simulation all the subsystem is considered to be in first order.

|                | Case I | Case II | Case III | Case IV |
|----------------|--------|---------|----------|---------|
| Diesel Generator | ✓      | ✓       | ✓        | ✓       |
| Fuel Cell       | -      | ✓       | ✓        | -       |
| Aqua Electrolyzer | -     | ✓       | ✓        | -       |
| Battery         | -      | -       | -        | ✓       |
| Wind Turbine    | ✓      | ✓       | □        | ✓       |
Wind Turbine Generator (WTG)
The changes in speed of wind relies upon time and related to the past speed. A few models of wind speed have been established and utilized. In this paper Auto Regressive Moving Average (ARMA) model is utilized, in which the wind speed is represented by ARMA time-series which is given as [7]:

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \cdots + \phi_n y_{t-n} + \alpha_t - \theta_1 \alpha_{t-1} - \theta_2 \alpha_{t-2} - \cdots - \theta_m \alpha_{t-m} \quad (1)$$

Where, $\phi_i$ is autoregressive parameter in which $i$ varies from 1 to $n$. $\theta_j$ is moving average parameter in which $j$ varies from 1 to $m$. $\alpha_t$ is noise parameter with zero mean. The simulated wind speed $SW_t$ can be calculated using the following equation [6]:

$$SW_t = \mu_t + \sigma_t y_t \quad (2)$$

Where, $\mu_t$ is average wind speed and $\sigma_t$ is standard deviation.

Aqua Electrolyzer (AE)
Electrolysis is used for the production of hydrogen by absorbing any fluctuations in the output power from WTG by aqua electrolyzers. The produced hydrogen is kept within the hydrogen tank and utilized by fuel cells. The requirement of the load is fulfilled by total output from WTG, DEG and FC. The transfer function of the aqua electrolyzer system is given as follows [5]:

$$P_{AE}(s) = \frac{K_{AE}}{1+sT_{AE}} \quad (3)$$

Where, $K$ is the gain and $T$ is time constants of system.

Fuel Cell (FC)
The fuel cell generates electric power by reverse electrolysis; that is the reaction of oxygen and hydrogen which forms water. It is similar to the oxidation/reduction process of a battery. In fuel cell, reaction takes place in fuel (not in electrodes)[8]. In the past few years, fuel cell generation have gained more attention due to the advantages, such as onsite installation, diversity of fuels, low pollution, reusability of exhaust heat and high efficiency. The transfer function of the fuel cell generation system is given as follows [5]:

Fig: 1. Block diagram of proposed hybrid power system [6].
\[ P_{FC}(s) = \frac{K_{FC}}{1 + sT_{FC}} \]  \hspace{1cm} (4)

Where, \( K \) is the gain and \( T \) is time constants of system.

**Diesel Engine Generator (DEG)**

A DEG consists of diesel engine and electric generator to provide electrical energy and various ancillary devices, such as control systems, circuit breakers etc. Diesel engine generator can produce steady and reliable electrical energy at required voltages and power levels [9]. During power outages, emergency backup electrical generators powered by diesel engine provide reliable, immediate and full-strength electric power. The transfer function is given as follows:

\[ P_{DEG}(s) = \frac{K_{DEG}}{1 + sT_{DEG}} \]  \hspace{1cm} (5)

Where, \( K \) is the gain and \( T \) is time constants of system.

**Control Strategy**

The control strategy is obtained by controlling the power error which is the difference between the load demand \( (P_D) \) and net power generated \( (P_G) \) [6].

\[ P_G = P_w + P_{DEG} + P_{FC} - P_{AE} \]  \hspace{1cm} (6)

Change in power generation affect the frequency response in power systems. For an ideal system the relation between frequency and power deviation is given as following [5]:

\[ \Delta F = \frac{\Delta P}{k} \]  \hspace{1cm} (8)

Where, \( \Delta P \) is the variation of generating power. 
\( k \) is the system frequency characteristic constant.

In a practical system, slow response is observed in the frequency. Hence equation (8) can be modified as [6]:

\[ \Delta F = \frac{1}{k(1+\tau s)} \]  \hspace{1cm} (9)

Equation (9) can also be represented as:

\[ \Delta F = \frac{1}{D + sM} \Delta P \]  \hspace{1cm} (10)

Where, \( M \) is inertia constant & \( D \) is damping constant.

**Table: 2. Parameters of the Hybrid System [6].**

| Gain       | Time Constant (sec) |
|------------|---------------------|
| \( K_{DEG} \) = 1 | \( T_{DEG} \) = 2  |
| \( K_{AE} \) = 1  | \( T_{AE} \) = 0.2  |
| \( K_{FC} \) = 1  | \( T_{FC} \) = 4    |
| \( K_{b} \) = 1   | \( T_{b} \) = 0.1   |
| \( D \) = 0.2     | \( M \) = 0.012     |

**PID Controller and Performance Index**

APID controller consist the arrangement for Proportional, Integral and Derivative actions, which attempts to minimize the error between a measured process variable and a desired set point. Transfer function of PID controller is given as:

\[ c(s) = K_p + \frac{K_i}{s} + K_d s \]  \hspace{1cm} (11)

Optimization of performance of the system can be carried out by adjusting performance index. Lower value of index is preferred for running a robust system. The performance index is defined as a
quantitative measure to indicate the system performance of the designed PID controller [10].

In control system, there are various performance indices viz. Integral Square Error (ISE), Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE) and Integral Time Square Error (ITSE) are utilized to estimate the performance of system [11, 12]. Since integral square error always results in positive error and it allows to discriminate over damped system from under damped system, hence it is used as fitness function to analyze performance of PID controllers. Using ISE, power error is calculated to design optimum system which is defined as:

\[
ISE = \int_0^t e^2 dt
\]

(12)

Where, \(e\) is power error obtained in the simulation time \(t\) and \(k\) is the variable in terms of the value of \(K_p\), \(K_i\) and \(K_d\). Limits taken for electrolyzer, fuel cell and DEG are from zero to 1.0, 0.3 and 0.8 per unit respectively.

**Particle Swarm Optimization (PSO)**

Swarm intelligence is a branch of nature inspired approaches which is used for function optimization. PSO is based on the combined nature of self-structured systems. It mimics the behaviors of bird flocking [13, 14]. PSO learn from the situation and practice it for solving the optimization problems. Particle used in PSO represents single solution in search space and is analogous to the bird. Every particle has a fitness value which is estimated by optimizing the fitness function. The particles also have velocities to direct its flying and all the particles go through the search area to obtain the best result by chasing the current optimum particle [4]. A basic flowchart of PSO is shown in Fig. 2 to explain its working.
Various steps for designing controller using PSO are:

**Step 1.** Initialization of a population of particles is done with arbitrary position and velocities in d dimension search space. Confining the search space by specifying the lower and upper bounds of every variable. The population is initialized with the velocity and position set to the predefined range and satisfying the equality and inequality constraints.

**Step 2.** In each iteration, the velocities of all particles are updated according to the equation (13)

$$V_{id}^{(t+1)} = wV_{id}^{(t)} + c_1 r_1 (p_{best id}^{(t)} - X_{id}^{(t)}) + c_2 r_2 (g_{best d}^{(t)} - X_{id}^{(t)})$$

Where $V_{id}^{(t+1)}$: velocity of particle i in d dimensional space

$X_{id}^{(t)}$: position of particle i in d dimensional space

$p_{best id}^{(t)}$: best position of individual i in d dimensional space until generation t

$g_{best d}^{(t)}$: best position of the group in d dimension until generation t

$w$: inertia weight factor controlling the dynamics of flying

$c_1$: cognitive parameter

$c_2$: social parameter

$r_1$ and $r_2$: random variables in the range [0,1]

**Step 3.** Every time after iteration, respective position of all particles is reorganized. This is done by using the following equation (14)

$$X_{id}^{(t+1)} = X_{id}^{(t)} + V_{id}^{(t+1)}$$

**Step 4.** Update particle best position $p_{best id}^{(t)}$ and globalbest position $g_{best d}^{(t)}$ using equation (15) and (16).

$$p_{best id}^{(t+1)} ← X_{id}^{(t+1)}$$ if $f(X_{id}^{(t+1)}) < f(p_{best id}^{(t)})$ (15)

$$g_{best d}^{(t+1)} ← X_{id}^{(t+1)}$$ if $f(X_{id}^{(t+1)}) < f(g_{best d}^{(t)})$ (16)

**Step 5.** The process continues to repeat from Step 2 to Step 4 until a sufficient good fitness is obtained. Otherwise, the process will automatically stop after reaching maximum set number of iterations. Once we get global best fitness, algorithm is then terminated.

### Table: 3. Parameters of PSO

| Parameter            | Value |
|----------------------|-------|
| Swarm Size           | 30    |
| Maximum no. of Iteration | 200   |
| Cognitive Component  | 1.414 |
| Social Component     | 1.414 |
| Inertia Weight       | 0.8   |

**CASE STUDIES**

In this section, different case studies of hybrid power system are presented with performed simulations and results are discussed. For showing its effectiveness, a series of simulation are done to prove its working for different combinations of generation components.

**Case I.** This case consists of diesel generator and wind turbine generator. In order to achieve balance between generation and load, sum of both the power error and frequency error is given to PID controller. Here, PID controller is tuned using PSO for the optimization of system. Along with the parameters of PID controller, gain $K_g$ present in the feedback loop is also optimized in algorithm. All calculations done based on per unit (pu) system.
Case II. This case consists of DEG, FC generators, WTG, and AE. Working procedure of case II is same as case I. Here, three separate PID controllers are provided for AE, FC and DEG. Also gains from frequency feedback are included in optimization process.

Case III. The components required for Case III are same as of case II. Thus, this case also consists of DEG, FC generators, WTG and AE. However, the components are connected in a different way in this case. In case III, the entire output of WTG is given to AE for electrolysis. Hence, only DEG and FC generators supply to fulfill the required load.

Case IV. In this case wind power, battery and diesel engine generators contribute to supply the load. Working procedure of system is same as explained in case I. The transfer function for battery is given below [4]:

\[ P_b(s) = \frac{K_b}{1+sT_b} \]  \hspace{1cm} (17)

Where, \( K \) is the gain and \( T \) is time constants of system. Also, limits for controller of battery is considered as \( \pm 0.5 \) per unit.

SIMULATION RESULTS

In this section, simulation results of the several studied cases and their analysis is given. Simulation time of 120 sec and sampling time is taken as 20 msec for each case. Also, power demand is constant at 1.0 per unit. For DEG a delay of 20 sec is taken as it does not respond instantaneously.

Case I. From Fig. 3 it can be noticed that DEG and WTG contribute 0.4 pu and 0.6 pu power respectively so that total power generation will reach to power demand i.e. 1 pu. Also, when output from the WTG changes unexpectedly, this system is unable to provide high-quality power to the load. The reason is that diesel generators have very large time constant. Thus, DEG does not provide immediate response to load demand.

Case II. From Fig. 4 it can be noticed that DEG, WTG and FC contribute 0.38 pu, 0.6 pu and 0.02 pu power respectively, so that total power generation will reach to power demand i.e. 1 pu. Power generated by aqua electrolyzer is not considered, as it provides input power to fuel cell and does not contribute directly to power generation. Also, the error in the power required is huge when the power generated by WTG varies quickly over a broad range. Though, the error in required supply turns out to be around zero and the system is able to provide sufficient power to meet required load. Time constant of aqua electrolyzers for power utilization is small so, these are used to absorb the variations in WTG output power. Thus, this system can deliver high-quality power to load when the output of wind turbines varies rapidly. In similar way, this system controls the frequency appropriately.
Case III. It can be clearly seen from Fig. 5 that DEG and FC contribute 0.8 pu and 0.2 pu power respectively, so that total power generation will reach to power demand i.e. 1 pu. Power generated by aqua electrolyzer is not considered, as it provides input power to fuel cell and does not contribute directly to power generation. Also, there is no fluctuation in total power generation due to absence of wind effect. From above results, it can be noticed that rapid variation in generated power by WTG affects the error in supply demand and turn out to be zero, as entire output power of WTG is utilized in electrolysis. Thus, for this system it is possible to provide very high-quality power to the load requirement with sudden changes in wind turbine output power.

Case IV. From Fig. 6 it is observed that WTG and battery contribute 0.6 pu and 0.4 pu power respectively so that total power generation will reach to power demand i.e. 1 pu. Also, DEG generation reaches to zero as soon as battery supply to its maximum power. From the results, it can be noticed that this system is also able to provide good quality power to fulfill the required load, with sudden change in wind turbine generator output. But use of battery is limited by its charging/discharging capacity and inverter capacity. Here, it is considered that, if the battery power goes below 50% then it injuncts discharge operation and when battery power reaches above 100% it injuncts charge operation.

Fig: 3. Case I. (a) Total power generated, (b) Frequency Deviation, (c) Power generated by wind turbine generator, (d) Power generated by Diesel engine generator
Fig: 4. Case II. (a) Total power generated, (b) Frequency Deviation, (c) Power generated by diesel engine generator, (d) Power generated by wind turbine generator, (e) Power generated by fuel cell, (f) Power generated by aqua electrolyzer.

Fig: 5. Case III. (a) Total power generated, (b) Frequency Deviation, (c) Power generated by diesel engine generator, (d) Power generated by fuel cell
DISCUSSIONS

From the simulation results, it is clear that in Case I simulation, the system is the least expensive system in comparison to other systems but in case of sudden change in wind speed or wind turbine output power, it is unable to deliver good quality power to the load. For system of case III, it is possible to deliver very high-quality power to the load demand with sudden changes in wind turbine output power. But overall performance is not effective, as the entire output of wind generator is utilized in electrolysis. The system of case IV can provide high quality power to the load but the system is expensive as it contains battery with large capacity. The lifespan of battery is very small due to frequent charging and discharging operation. The hybrid system of case II provides high quality power in comparison to case I and it is most effective and less expensive system in comparison to case III and case IV systems. The frequency response characteristics presented in Table 4 with peak value and settling time shows that system of case II provides good frequency response with the tuning of PID controllers. Also, global best settles on minimum value in case II as compared to other cases. Hence it provides better convergence.

Table: 4. Comparison of frequency response of all the four cases on different parameters.

| CASE    | PEAK VALUE | SETTLING TIME (sec) | GLOBAL BEST |
|---------|------------|---------------------|-------------|
| CASE I  | 1.64       | 102                 | 11.9        |
| CASE II | 1.35       | 70                  | 10.1        |
| CASE III| 7.67       | 110                 | 112.8       |
| CASE IV | 0.12       | 80                  | 22.5        |
CONCLUSION
Based on results obtained, it can be concluded that, by using optimized parameters, the hybrid power system provides high quality power with minimum deviations. It is also clear that, of the four-system studied with different combinations of its subsystems, the system which uses WTG, AE, FC with DEG gives the best results and also settles faster (minimum global best) than other cases. The future work would be towards: system sizing, economic analysis, operations and maintenance practices. Hybrid power systems which would be developed are to be feasible with viable options with the added benefit of being environmentally friendly and ensured safety.

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