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Enhanced Non-linear PID-Based on Virtual Inertia Control to Enhance the Frequency Stability of a Hybrid Power System

Ahmed H. Mohamed[(a)*], Helmy M. El Zoghby[(a)], Mohiy Bahgat[(a)], A. M. Abdel Ghany[(a,b)]

[(a)*]Department of Electric power and machines, Faculty of Engineering, Helwan University, Cairo, Egypt.

[(b)]Department of Electric power and machines, Higher Engineering Institute, Thebes Academy.

*Corresponding Author: Ahmedhamada215@gmail.com

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ABSTRACT

The loss of system inertia caused by the replacement of conventional generating units with a high number of renewable energy sources (RESs) has an unfavorable impact on the power system's frequency stability, resulting in the power system's weakening. A low inertia hybrid power system may have a high frequency oscillation and have a real challenge to maintaining frequency stability under different operating conditions. To enhance the single area hybrid power system's frequency stability and save it from blackout, this paper introduces Enhanced Non-linear PID (ENLPID) based on virtual inertia control (VIC) for a single area hybrid power system with a high contribution of RESs. The ENLPID based on VIC has a great effect in enhancing the frequency stability of the studied hybrid power system. This effect is remarkable in saving the frequency stability, limiting the frequency deviation, and handling the different contingency conditions. The ENLPID based on VIC response is compared to optimal non-linear PID (NLPID) based on VIC, optimal PID based on VIC, and conventional VIC (CVIC) responses. Moreover, these responses of control techniques based on VIC are compared with the response of the studied single area hybrid power system without VIC by using MATLAB ^{TM}/Simulink, that to prove the enhancement in the frequency stability of the studied single area hybrid power system when using the ENLPID based on VIC. This comparison shows the effect of using the VIC concept in saving the hybrid power system stability and the role of ENLPID in improving the frequency response of the system. To achieve the optimal parameters of the ENLPID based on VIC, the particle swarm optimization (PSO) technique is used.

Keywords: virtual inertial control, ENLPID controller, NLPID controller, Frequency stability, RESs, PSO.

1 INTRODUCTION

Nowadays, due to the energy crisis and environmental concerns, it is become necessary to increase the renewable energy sources (RESs) contribution in the power system. increasing the RESs contribution effects in the number of the conventional generation units which provide the power system inertia from its stored kinetic energy in its rotating mass [1]. Moreover, the inverters-based RESs have no present or low contribution to the system inertia [2]. So, the increase in the RESs' contribution decreases the full power system inertia. That could cause significant frequency stability concerns in the hybrid power system [3]. The frequency stability problems could limit the penetration of the RESs. Moreover, the low inertia hybrid power system may have high frequency oscillation due to the sudden change in generation or load power, which can lead to the loss of the system stability or a blackout [4].

The VIC concept is present to handle the hybrid power system voltage and frequency control issues due to the leakage in the system inertia. Its idea depended on imitating the response of a traditional generator, which enhances the system inertia. That imitating can be achieved by applying VIC to power inverters and energy storage systems (ESS). So, VIC enhance the frequency stability of the system and allow for more contribution of RESs [5].

Many control strategies have been implemented based on the VIC concept. In [6], the dynamic performance of a microgrid is enhanced by using a virtual inertia system based on derivative controlled solar and energy storage. An isolated microgrid with high RESs penetration uses proportional-integral (PI) -based VIC to reduce frequency variations and improve its stability [5]. The VIC Technique is used for enhancing DC microgrid damping performance with a negative feedback effect [7]. A distributed VIC is presented to improve the inertia of the DC microgrid while reducing the DC voltage change rate [8]. [9] introduces a VIC for regulating a DC microgrid's bus voltage and inertia enhancing in both grid-connected and isolated operation. wind turbine generators Nonlinear VIC for Improving Primary Frequency Response in [10]. Also, the VIC can be implemented by using self-adaptive controllers as in [11] interconnected PV-based AC microgrid clusters use adjustable VIC of supercapacitors to enhance the dynamic stability. [12] uses virtual inertia to provide an adaptive frequency technique in multi-area microgrids that include renewable energy and electric vehicles. Virtual Inertia Using Fuzzy Logic Controlling variable-speed wind turbines with a doubly fed induction generator to improve the stability of a hybrid power system [13]. However, frequency stability still requires improvement, especially in the case of a single-area hybrid power system with a high-RESs contribution, to improve system stability and avoid blackouts.

This paper proposed two control techniques based on VIC to improve the frequency of the studied hybrid power system:

1- Non-linear PID (NLPID) controller
2- Enhanced Non-linear PID (ENLPID) controller

The NLPID controller gives the system more flexibility to handle disturbances and different operating conditions. That improves the studied system dynamic response and tries to treat the system's weakening due to increasing the RESs contributions. To prove the efficiency of the proposed control techniques, MATLABTM/Simulink is used to compare the responses of ENLPID based on VIC, NLPID based on VIC, optimal PID based on VIC, CVIC, and the system without VIC.

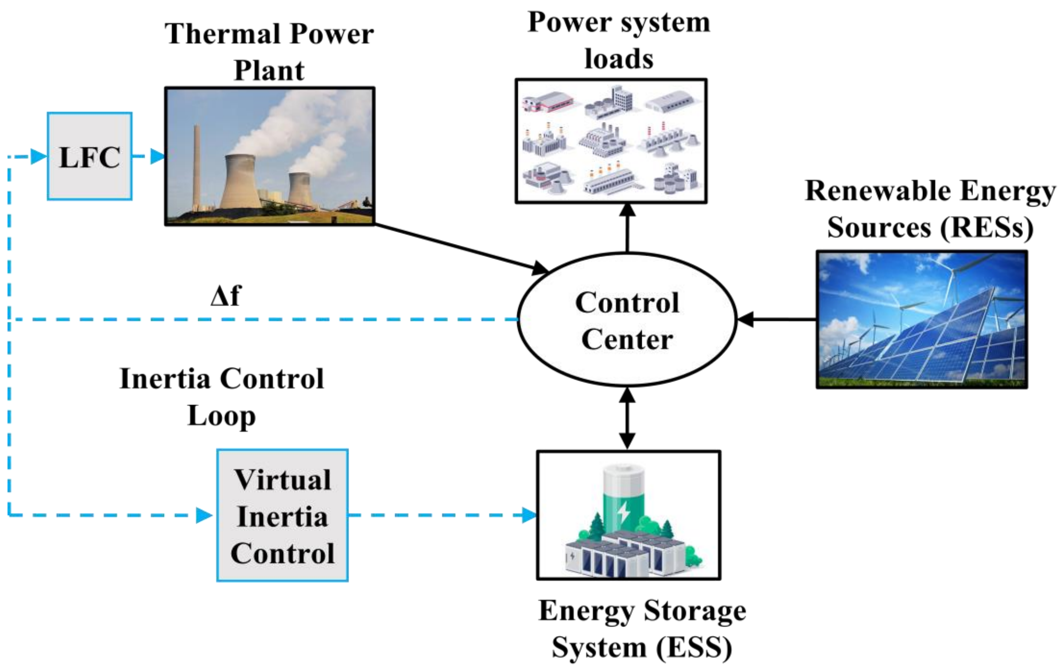


Fig. 1 Simplified studied single area hybrid power system

2 SYSTEM DESCRIPTION

The studied system is a small hybrid power system (base of 20 MW) that consists of a 20MW conventional energy source (non-reheat thermal power plant) and RESs, divided into an 8MW wind power plant and a 4MW solar power plant. Moreover, there is a load of 15MW and 5MW ESS as in Fig.1 [5].

When modeling the studied hybrid power system, the effects of physical constraints such as power plant generation rate constraints (GRC) are considered in this paper. The rate of produced power generation is limited by GRC, which is stated as 0.2p.u. MW/min for the non-reheat unit. Moreover, the turbine valve/gate limitations have been set to ±0.3 p.u.MW. The studied hybrid power system dynamic model is shown in Fig. 2 and its nominal parameter values are given in Table 1[5].

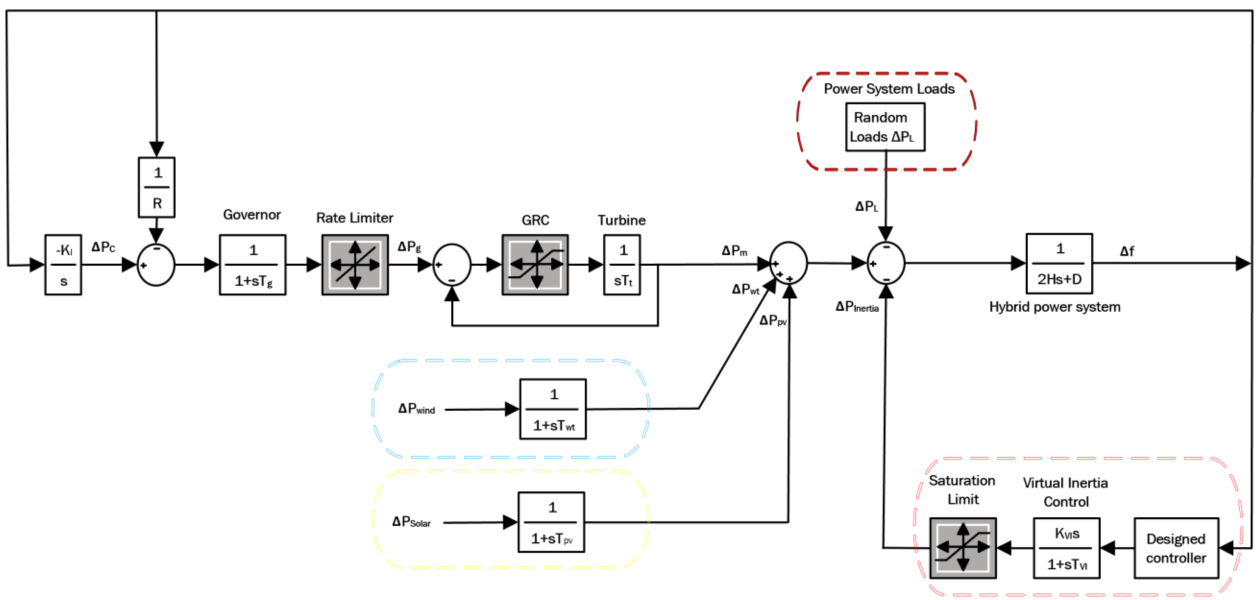


Fig. 2 The studied hybrid power system dynamic model.

Table 1 The nominal parameters values of the studied system.

Parameter	Ki	Tg	Tt	R (Hz/p.u.MW)	D (p.u.MW/Hz)	H (p.u.MW s)	TVI	Twt	Tpv	KVI
Value	0.05	0.1	0.4	2.4	0.015	0.083	10	1.5	1.8	0.5

2.1 VIC for the studied single-area hybrid power system

When the penetration level of RESs rises, it can have a significant effect on system inertia (H). RESs, on the other hand, exchange power with the power system via power electronic devices. Because RESs-based power electronic interfaces have no rotational mass, the related inertia is almost zero. As a result, the system's total inertia will decrease. While the RESs's contribution level rises, the frequency deviation also increases. To deal with this problem, virtual inertia control was implemented in the studied system. As shown in Fig.3, the virtual inertia control uses the rate of change of frequency (RoCoF) to add active power to the set point to simulate the system inertia response [5][12].

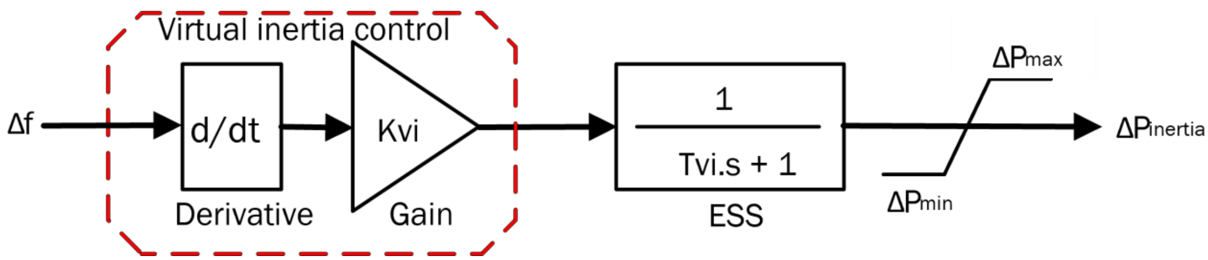


Fig. 3 Model of VIC.

This paper investigates the use of VIC based on NLPID and ENLPID controllers with single area hybrid power systems, as well as their role in improving the system frequency stability under contingency conditions such as sudden connecting or disconnecting of a large load in the presence of high RESs contribution.

2.2 Non-linear PID-based VIC.

The linear PID controller's output time response is:

$$u(t) = K_p\, e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{1}$$

where Kp, Ki, and kd represent proportional, integral, and differential gains, respectively. When the system is more complicated, the fixed parameters in a traditional PID controller are not efficient enough to control the system. The performance of linear PID controllers can be improved by using non-linear PID (NLPID) controller, which is suitable and successful method for many applications [14]. The parameters of a nonlinear PID (NLPID) controller are considered to be dependent on the amount of system error. A nonlinear combination can give more flexibility to the system, allowing it to perform substantially better. Nonlinear PID (NLPID) can increase control quality by achieving good static and dynamic performance [15-16]. As shown in Fig. 4, the NLPID controller has fixed gains Kp, Ki and Kd (traditional PID controller gains) and a nonlinear gain Kn(e). The output u(t) of a nonlinear PID controller is defined as:

$$u(t) = K_n(e)[\, K_p\, e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}] \tag{2}$$

The nonlinear gain is a function of the error (e), so it has a high initial value and continues with a low gain. The high initial value aids in achieving a fast dynamic response and the low gain after that aids in avoiding unstable behavior. The nonlinear gain is defined as [14] [17-18]:

$$\mathrm{Kn(e)} = \frac{(\exp(\mathrm{g.e}) + \exp(-\mathrm{g.e}))}{2} \tag{3}$$

g: describes the rate of variation of $Kn(e)$ (positive constant).

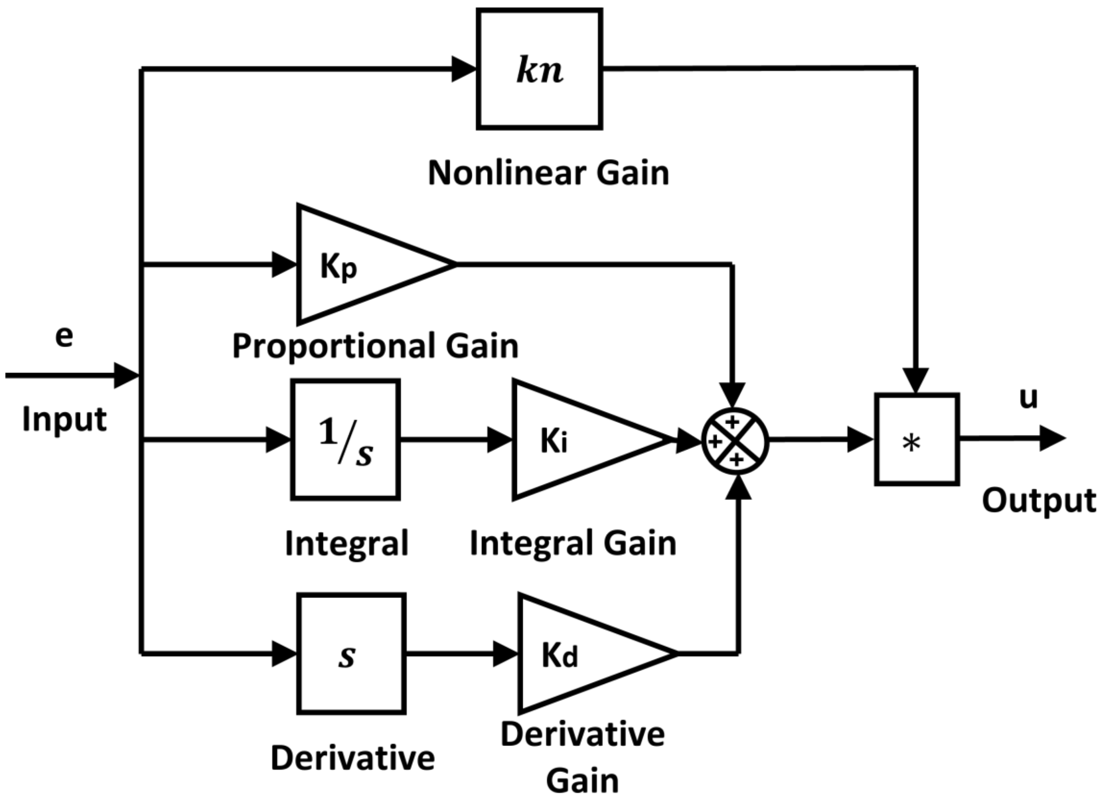


Fig. 4 Model of the NLPID Controller.

Particle swarm optimization (PSO) is used to determine the optimal values for NLPID controller parameters to reduce system frequency deviation and thereby improve power system stability.

2.3 Particle Swarm Optimization (PSO)

PSO is a simple, fast and intelligent searching technique. Moreover, PSO is easy to use, requires less storage, has high convergence rates, and is less dependent on a set of initial values, indicating robustness [5]. PSO is used to determine the optimal PI controller parameters for minimizing system frequency deviation in [5]. Moreover, the parameters of the PID controller that is used in LFC in [19] are obtained by using PSO.

Kennedy and Eberhart first proposed the PSO in 1995 [20]. It is an evolutionary computation-based global optimization technique. This optimization technique's main operation idea was established on a flock of flocking birds. Birds are either dispersed or move from place to place in search of food. Furthermore, food can be discovered since it is brought by other birds at any time during the search for food [21]. Instead of using evolutionary operators, individuals known as particles are used in this optimization strategy. A swarm is made up of a number of particles, each of which represents a possible solution to the problem. Every particle in the PSO algorithm flies through the search space based on its own flying knowledge and the flying background of its friends. In the D-dimension search space, each particle is treated as a particle. Xi represents the particle's position. The best previous mode of any particle is saved and referred to as the Pbest. In the meantime, another best value (i.e., the overall best value gbest) is followed by a global version of the PSO algorithm [22]. vi represents the particle velocity i and all particles are updated according to the following equations:

$$v_{id}^{n+1} = \mathrm{w}.V_{id}^{n} + c_1.\mathrm{rand}().(P_{id}^{n} - X_{id}^{n}) + c_2.\mathrm{rand}().(P_{gd}^{n} - X_{id}^{n}) \tag{4}$$

$$x_{id}^{n+1} = x_{id}^{n} + v_{id}^{n} \tag{5}$$

These equations are used to calculate the new velocity and position values of each particle based on its previous values. The optimization technique's learning parameters have a substantial impact on the algorithm's convergence rate. The main objective of the PSO method in this paper is to improve the frequency stability by determining the optimal parameters of a proposed VIC. As a result, Fig.5 shows the flowchart of the suggested PSO algorithm for optimum NLPID based on VIC parameters (i.e., Kp, Ki, Kd and g). From the viewpoint of stability, the range of controller gains is determined.

$$Kp^{min} \le Kp \le Kp^{max}$$
$$Ki^{min} \le Ki \le Ki^{max}$$
$$Kd^{min} \le Kd \le Kd^{max}$$
$$g^{min} \le g \le g^{max}$$

The suggested optimization technique employs integral time absolute error (ITAE) as an objective function, which may be expressed as follows:

$$\mathrm{ITAE} = \int t.|\Delta f|\mathrm{dt} \tag{6}$$

Table 2 shows the optimum NLPID based on VIC parameter values.

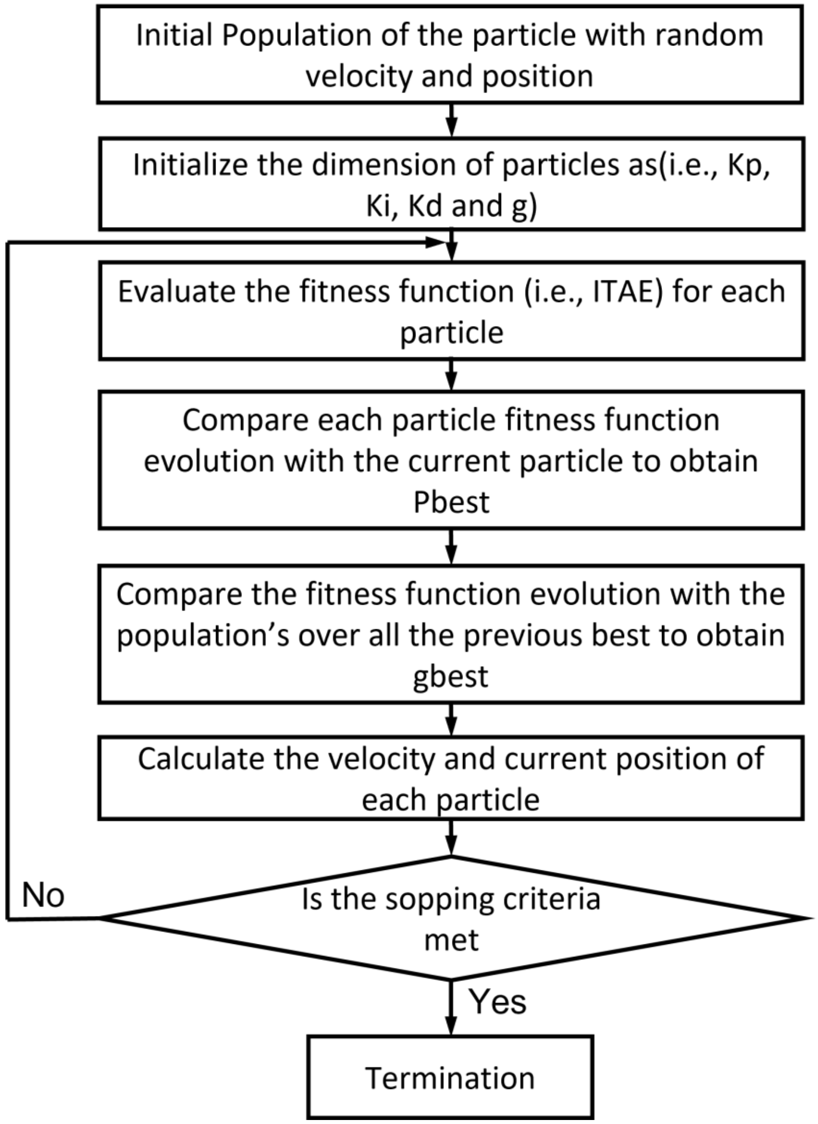


Fig. 5 Flowchart of PSO- NLPID based on VIC.

Table 2 The optimal gain values of the NLPID controller.

Parameter	**Value**
K_p	**15**
K_i	**35.88**
K_d	**0.001**
g	**0.0014**

2.4 Enhanced non-linear PID-based VIC.

The performance of the NLPID controller is improved by using an enhanced non-linear PID (ENLPID) controller. Because the proposed ENLPID controller considered the nonlinear gain $Kn(e)$ as a row vector can expressed as [14][18]:

$$K_n(e) = [K_{n1}(e) \quad K_{n2}(e) \quad K_{n3}(e)] \tag{7}$$

By this way, the ENLPID controller consists of two parts, as in Fig. 6:

1-The nonlinear gains $Kn(e)$.

2-A linear fixed gain PID controller (Kp, Ki, and Kd).

The nonlinear gain value varies depending on the error and the type of fixed parameters (Kp, Ki, and Kd). The output of ENLPID control can be described as in Eq. (8) [14][18]:

$$u(t) = K_p \,.\, K_{n1}(e)\,.\, e(t) + K_i \int_0^t K_{n2}(e)\,.\, e(t)\, dt + K_d \,.\, K_{n3}(e)\,.\, \frac{de(t)}{dt}] \tag{8}$$

In this paper, the nonlinear variables kn (e) are represented as an exponential function by the function of the error. kn(e) has a range of 0 to kn(e)max. The following equation represents the nonlinear variables knx (e) [14][18].

$$K_{nx}(e) = ch(g_x \; e) = \frac{(\exp(g_x . e) + \exp(-g_x . e))}{2} \tag{9}$$

Where x=1, 2, 3, up to ∞

$$e = \begin{cases} e & |e| \le e_{max} \\ e_{max} sgn_{(e)} & |e| > e_{max} \end{cases} \tag{10}$$

Where:

emax: the range of deviation.

gx: the rate of variation of Knx (e).

Table 3 shows the optimal values for the ENLPID controller parameters that are obtained by using PSO.

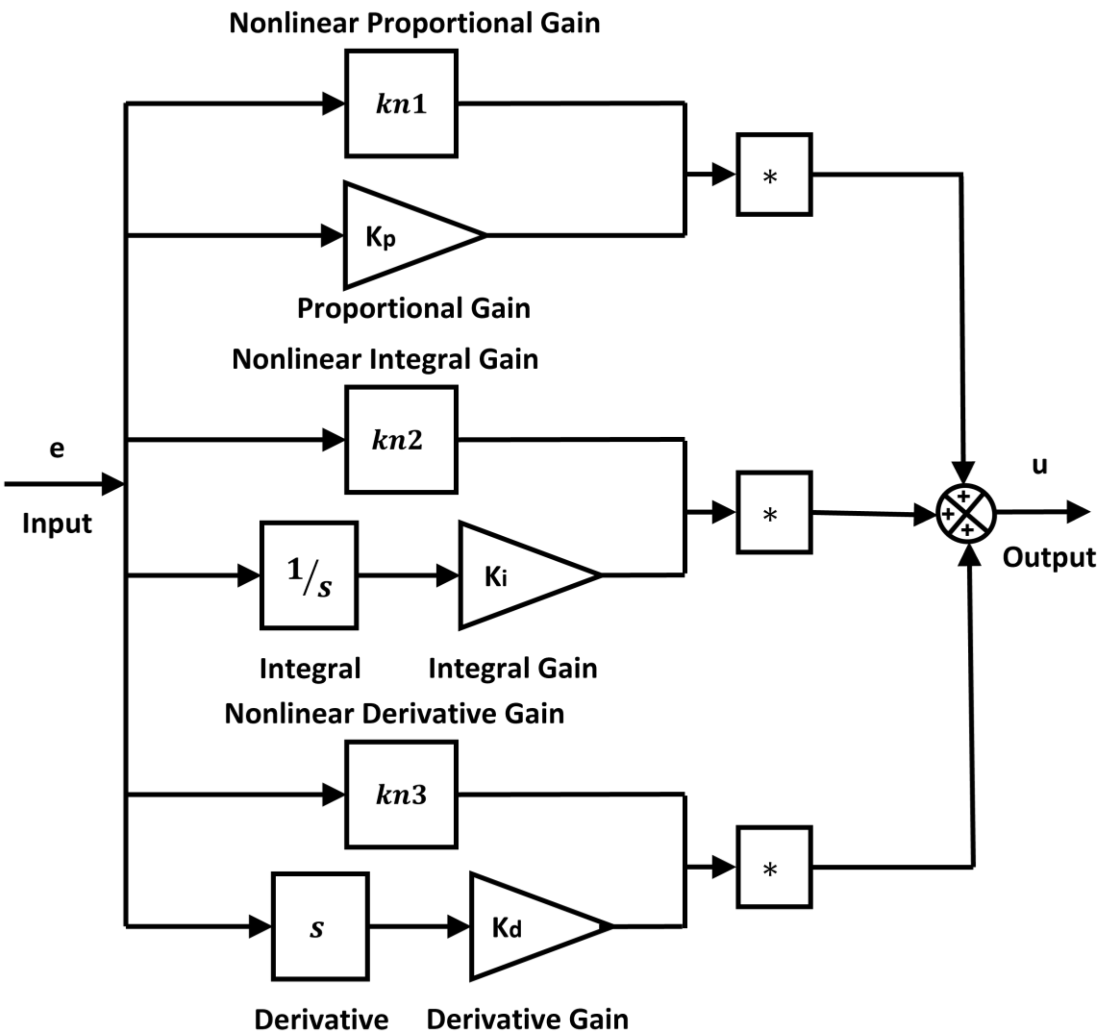


Fig. 6 Model of ENLPID Controller.

Table 3 The optimal gains values of the NLPID controller.

Parameter	Value
K_p	**36.2945**
K_i	**38.2436**
K_d	**0.6447**
g1	**0.0606**
g2	**0.4235**
g3	**0.5827**

3 SIMULATION RESULTS

In this section, the performance of the proposed virtual inertia controllers for the studied single area hybrid power system is evaluated using MATLAB^{TM}/Simulink. The controllers are tested under different conditions that include a high contribution of RESs.

Three test cases are employed to verify the performance of the proposed controllers. Furthermore, performance is compared between the proposed virtual inertia controllers (ENLPID based on VIC, NLPID based on VIC), PID based on VIC, the conventional virtual inertia control (CVIC)-based derivative control technique in [5], and the system without a virtual inertia controller. The optimal values of the PID parameters Kp, Ki, and Kd are 8.4539, 26.9225 and 0.0013.

3.1 Case1: full normal system inertia (H=100%)

A 0.2 pu step change in the load power is applied to the studied single area hybrid power system with full normal system inertia (H=100%). That change in load represents the connecting of a large load to the power system. So, this case shows the response of the system to this operating condition with full normal system inertia.

As shown in Table 4 and Fig. 7, the high fluctuation in the system frequency in the absence of VIC reaches ±0.757 Hz. The CVIC limits the frequency deviation to ±0.637Hz, and this shows the role of VIC. The frequency deviation was reduced significantly by using PID-based VIC, NLPID-based VIC, and ENLPID-based VIC, and this shows how

Table 4 Comparison between the over/undershoots and the settling time for the different control techniques in case1.

Controller	Peak overshoots	Peak Undershoots	Settling time (sec)
Without VIC	0	-0.757	25.9
CVIC	0	-0.637	26.7
PID-based VIC	0.0078	-0.219	1.04
NLPID-based VIC	0	-0.16	1.08
ENLPID-based VIC	0	-0.088	2.22

the proposed control techniques improve the frequency response of the system and enhance its stability. The ENLPID-based VIC shows good performance and has significantly improved the frequency performance. Moreover, it limits the frequency deviation value to only ±0.088Hz.

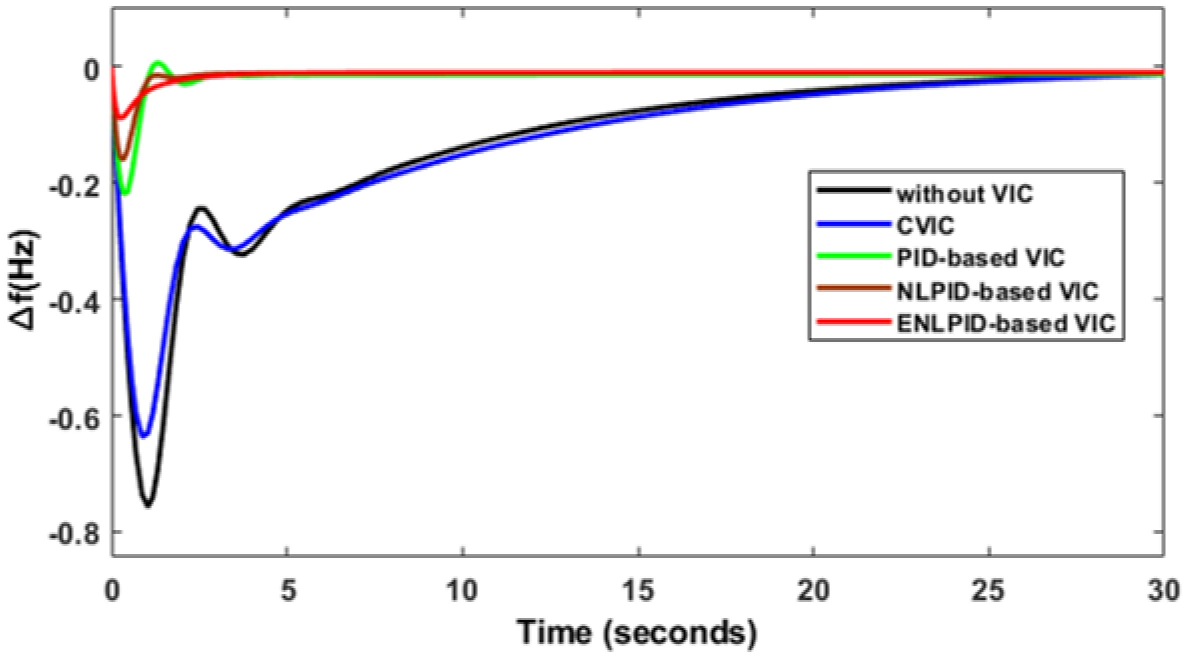


Fig. 7 Frequency response for case1.

3.2 Case2: medium system inertia (H=65% of normal)

The RESs penetration increases gradually, which leads to a reduction in the hybrid system's total inertia. In this case, the penetration of RESs increases until the total system inertia is reduced to 65% of normal system inertia (medium system inertia). The same load disturbance applied in case 1 (a 0.2 pu step change in the load power) is also applied in this case to show the effect of inertia reduction and this affect on the system frequency stability.

With increasing the RESs penetration the total system inertia decrease, that affects in the system frequency stability. As shown in Table 5 and Fig. 8, without VIC, the frequency deviations become more than ±1 Hz. The effect of VIC is significant in limiting the frequency deviations. Using the ENLPID-based VIC, the frequency deviations are limited to ±0.092 Hz (the lowest frequency deviation). That is, the ENLPID-based VIC provides a stable performance that is only slightly affected by the system inertia reduction in this case.

Table 5 Comparison between the over/undershoots and the settling time for the different control techniques in case2.

Controller	Peak overshoots	Peak Undershoots	Settling time (sec)
Without VIC	0.30	-1.11	25.8
CVIC	0	-0.868	26.4
PID-based VIC	0.002	-0.253	2.17
NLPID-based VIC	0	-0.177	1.73
ENLPID-based VIC	0	-0.092	2.22

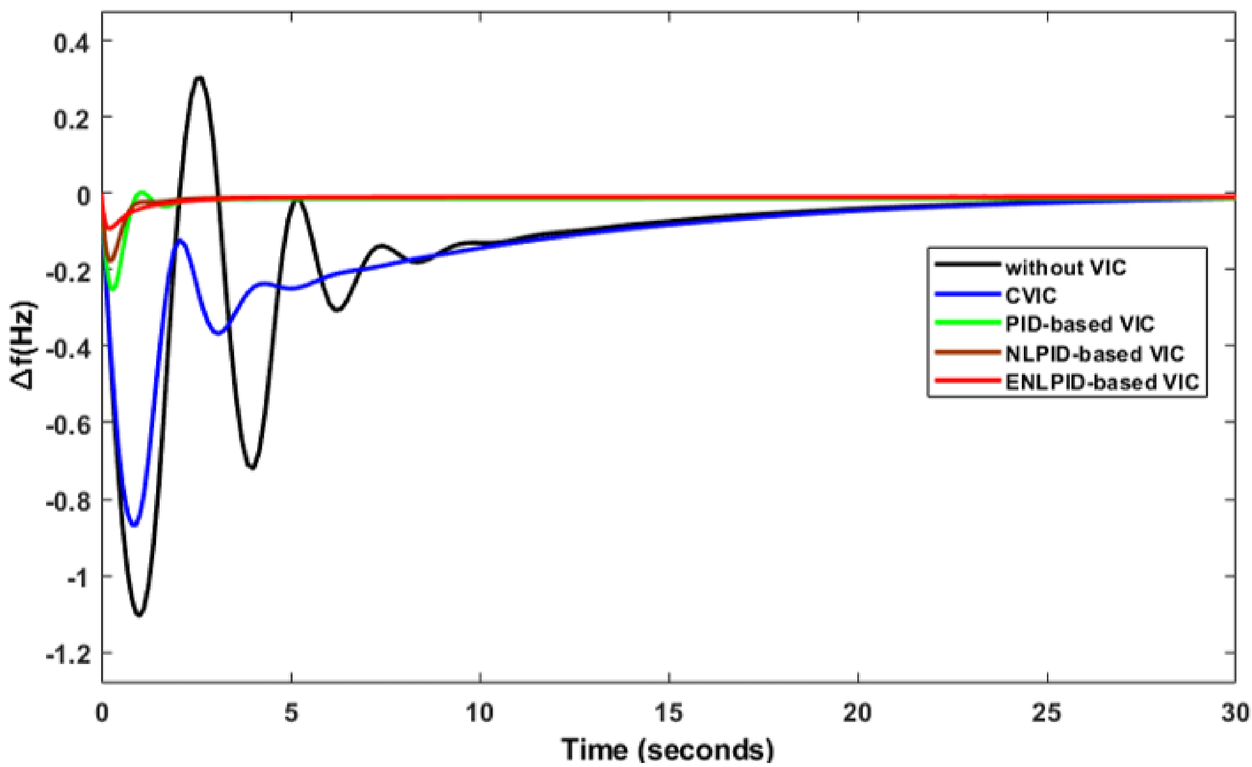


Fig. 8 Frequency response for case2.

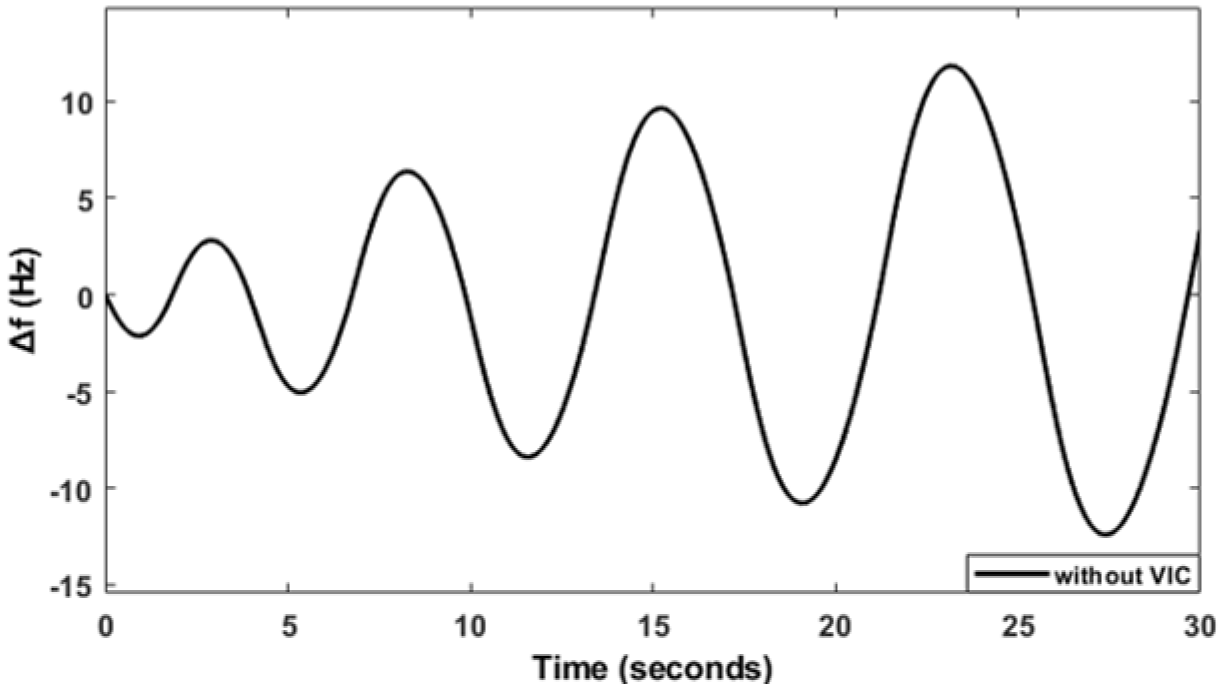
3.3 Case3: Low system inertia (H=30% of normal)

The percentage of the RESs contribution in the hybrid system is increased till the total system inertia becomes 30% of the normal system inertia. So, the studied single area hybrid power system becomes a low-inertia system. In case3, the same load disturbance (a 0.2 pu step change in the load power) is applied as in the other cases to show the performance of the different proposed controllers with the low inertia system.

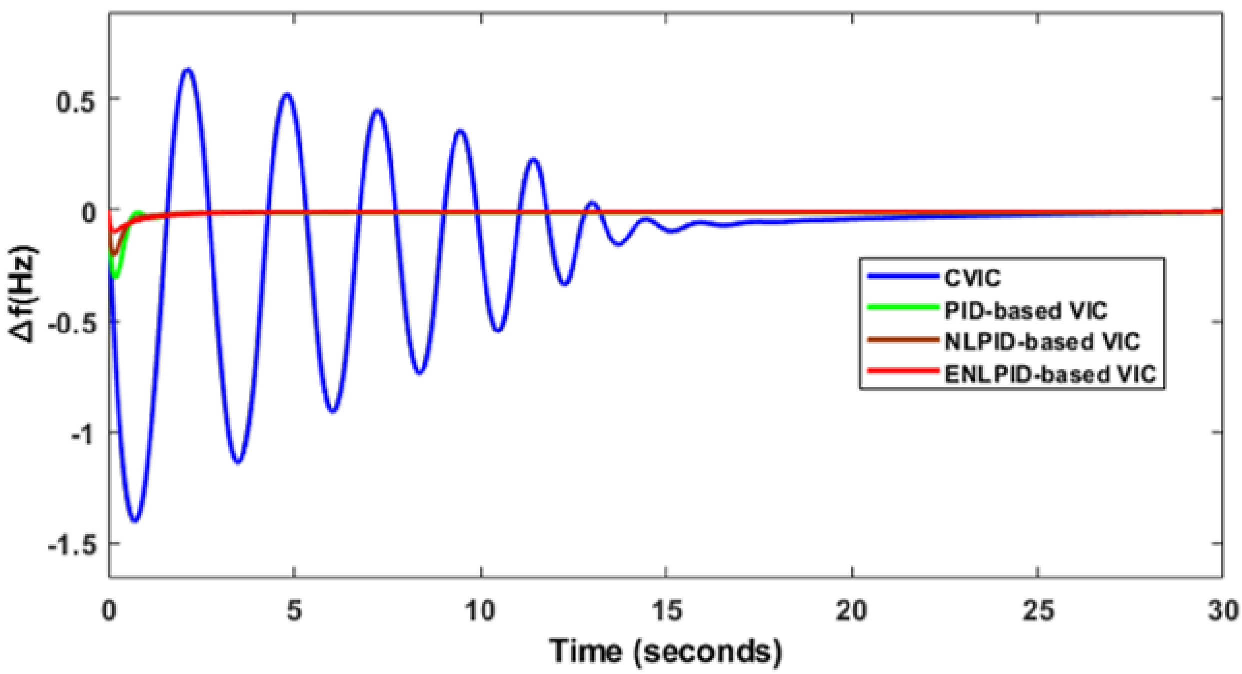
The reduction in the total system inertia affects the stability of the system. In this case, the hybrid power system is weak and can not handle the disturbance. That can lead to a blackout. VIC is used to enhance the single area hybrid power system's stability and prevent a blackout. Table 6 and Fig. 9 show the impact of system inertia reduction on the system frequency performance. Without VIC, the hybrid power system could not handle the disturbance. While the other controllers based on VIC can save the microgrid stability with different frequency deviations and settling time. The CVIC saves the hybrid power system stability, but with a high frequency deviation of up to ±1.406 Hz and a long settling time. While the proposed control techniques limit the frequency deviation to small values reach ±0.097 Hz by ENLPID-based VIC. The ENLPID-based VIC prevents a blackout, enhances the single area hybrid power system stability, and minimizes frequency deviation to the lowest value. That allows for more contributions from RESs while saving the hybrid power system stability.

Table 6 Comparison between the over/undershoots and the settling time for the different control techniques in case3.

Controller	Peak overshoots	Peak Undershoots	Settling time (sec)
Without VIC	-	-	-
CVIC	0.636	-1.406	25.8
PID-based VIC	0	-0.308	2.06
NLPID-based VIC	0	-0.204	1.68
ENLPID-based VIC	0	-0.097	2.22



(a)



(b)

Fig. 9 Frequency response for case3.

4 CONCLUSION

The RESs penetration is increased, and that decreases the system's total inertia. So, saving the stability of the hybrid power system and improving the frequency performance has become more difficult. The VIC concept is used to handle this issue by simulating the inertia characteristics of traditional generators and supporting the system at the contingency condition based on calculating the ROCOF. This paper studies the design of ENLPID based on VIC, NLPID based on VIC for a single area hybrid power system. PSO is used to obtain the optimal control technique parameters. ENLPID based on VIC is used to improve the stability and the dynamic response of the studied system. Moreover, it has a low-frequency deviation. That allows for increased RESs penetration. Moreover, ENLPID based on VIC proves its efficiency when it is compared with different control techniques.

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