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Proportional Resonant Controller-Based Virtual Powerplant with improved Dynamic Response in Distribution Network

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Abstract

The concept of Virtual Power Plant (VPP) emerges as a pivotal advancement in power systems engineering, aiming to enhance the integration of renewable energy sources into the power market. This research delves into the challenges faced by Distributed Energy Resources (DERs), such as power losses, voltage variations, and revenue losses in the distribution network, hindering the effective participation of small-scale renewable energy sources in the power market. Furthermore, the research addresses the challenge of poor dynamic response in VPPs attributed to dynamic loads and DER characteristics. To mitigate this, a Proportional Resonant (PR) controller is proposed to enhance the dynamic performance of the VPP. Comparative analysis with the conventional Fractional Order Proportional Integral Derivative (FOPID) controller reveals the superiority of the PR controller. The PR-controlled VPP exhibits improved dynamic performance with a lower settling time of 0.49 seconds and a reduced steady-state error of 2.78 compared to the FOPID controller. The investigations extend to the comparison of voltage, real power, and reactive power between the FOPID and PR controllers. The results underscore the superior response of the PR-controlled VPP, showcasing its efficacy in achieving faster responses and minimizing spikes in voltage and power variables.

Keywords: Polynomials; Collocation method; Successive integration technique; Neutral delay differential equations.

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1. Introduction

The requirement for electrical energy is increasing every year around the world. Smart and automatic applications, recent advances in telecommunications, industrial developments, and electric vehicles are the reasons for increasing power demand [1]. The increase in population growth is also one of the major concerns for electrical demand. The report of the Internal Energy Agency shows that the population is increasing at an annual rate of 1.2 % compared to the previous year, and the requirement for energy consumption is rising at an annual rate of 1.9 % compared with last year [2]. The world started to utilize electrical power from Renewable Energy Sources (RES) to avoid the difficulties of conventional

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resources. Globally, solar and wind are largely focused on generating electricity [3]. At the end of 2019, the installed solar energy was 627 GW with 15 % annual growth and the installed wind energy was 651 GW with 10 % annual growth [4]. The world knows the importance of RES due to the insufficient, pollution, and high cost of conventional energy sources [5]. The problem and challenge of non-conventional energy sources have been resolved by integrating diverse renewable sources in one way known as Virtual Power Plant (VPP) [6]. It can integrate the various distributed generators, regulate the storage devices, and control the load by Information Communication Technology (ICT) [7].

An idea for a Virtual Power Plant (VPP) is expanding globally, and several nations have launched tiny projects based on it [8]. Some scholars refer to the VPP as a virtual utility. The petrol and electrical industries helped develop the VPP in Europe [9]. The fuel cell-based VPP is connected to small homes, commercial buildings, and household applications [10]. The public utility sector created a Virtual Power Plant (VPP) in Germany using Energie-Umwelt-Service (EUS) to coordinate and operate DG units from multiple locations [11]. According to the International Gas Union, VPP is a combination of small distributed generators powered by sources of clean energy, fuel cell technology, grid-connected power supplies, storage units, and small and medium power and heating systems [12] that are managed and coordinated for a single goal by cutting-edge technology and communication [13]. Little and medium-sized family homes, and low and medium-volume commercial, and industrial applications may be connected to this VPP [14,15].

In this paper, Section 2 describes the structure and operation of a VPP with a block diagram. The source and load types of the virtual power plant are explained with a suitable diagram. Section 3 elaborates on the problem that arises in VPP due to uncertain conditions. Fractional Order Proportional Integral Derivative (FOPID) is identified as a suitable controller to solve the uncertainty problems in VPP. The operation of VPP with FOPID controller and their output of RMS voltage, real power, and reactive power are analysed with simulations. Section 4 enumerates the concepts of a Proportional Resonant (PR) controller-based VPP system. Section 5 presents the simulation results of both controllers are discussed with their results. Time domain parameters of FOPID and PR controller are compared. With appropriate outcomes, the profile of the VPP system's voltage, active power, and reactive power is reviewed. Section 6 shows the conclusion and future scope of the proposed controller in VPP to improve the responses in the distribution network.

2. Proposed Structure of Virtual Power Plant

Environmental protection requires the development of virtual power plants to decrease pollution and produce green energy from renewable energy sources [16]. An appropriate block diagram is used to demonstrate the idea and functioning of the virtual power plant in terms of generation, transmission, and distribution [17]. To lower the amount of energy purchased from conventional power plants, small-scale renewable energy source plants can engage in the energy market as a single power plant. It is a novel concept for the distribution side of the energy management system [18]. VPP is used to combine many energy sources, including grid electricity, solar, wind, and energy storage. To the load, VPP functions as a single power plant [19]. Fig. 1 depicts the VPP block diagram in its generic form. Based on the operation, the suggested VPP may be divided into source-side VPP and load-side VPP [20]. Some renewable energy sources used in source-side VPP include solar PV panels, wind turbines, battery storage, and grid electricity. Depending on the operation, different loads and load sides make up the load-side VPP [21]. Both home and industrial loads are taken into account in the load-side VPP in this study. Every RES is monitored using the source-side VPP, and the generating power of each RES may be projected independently based on various climatic conditions. The wind farm does not always provide power continuously. Wind energy generation varies depending on the local wind patterns. Based on the previously recorded values of wind circulation in the area, tower height, number, and blade size, source-side VPP is used in wind plants to anticipate the production power for the subsequent 24 h, generating power through continuous load-side monitoring and distribution based on load demand. If the amount of electricity generated by the wind is greater than what is needed to power the load, a battery may be attached. the origin side based on the measured values of solar panel inclination angle, environmental condition, and number of panels, VPP is also used to anticipate the producing power from solar panels. VPP distributes and monitors the solar electricity to the load side. When producing power exceeds load demand, solar electricity can be coupled to an energy storage device. Based on the operation, renewable energy sources, and load requirements, the battery is taken into account for charging and discharging. The battery is chosen based on the load needs and renewable energy sources. When renewable energy sources are producing more electricity than is needed by the load, the battery is charging. When there is a greater electricity demand that can be produced from renewable sources, the battery discharges. When electricity is generated from renewable sources and battery discharge is insufficient to fulfil load requirements, the grid power supply may be linked to the load side. The least amount of power from the grid is supplied according to the demands of the load. When RES generates more power than is required by the load, the grid supply may be supplemented via VPP with renewable energy. The power needs of the load are determined by the load side VPP, which includes several forms of load. Industrial and domestic loads are taken into account in load-side VPP. The power needs of industrial and home loads for the next 24 hours are predicted using the load side VPP. Based on previously observed load information, load-side VPP can forecast the power requirements of loads. Depending on the power requirements of the load, various renewable sources, batteries, and the grid may be linked to the load through the load side VPP [22].

The power usage and load demand are continually monitored by the load side VPP. When there is a significant electricity demand, the load side VPP is deployed to connect additional RES to the load by the necessary power. Other renewable sources may be connected to batteries and the grid's power supply if the power demand is lower. The load-side VPP is used to connect the bare minimum of RES to the load.

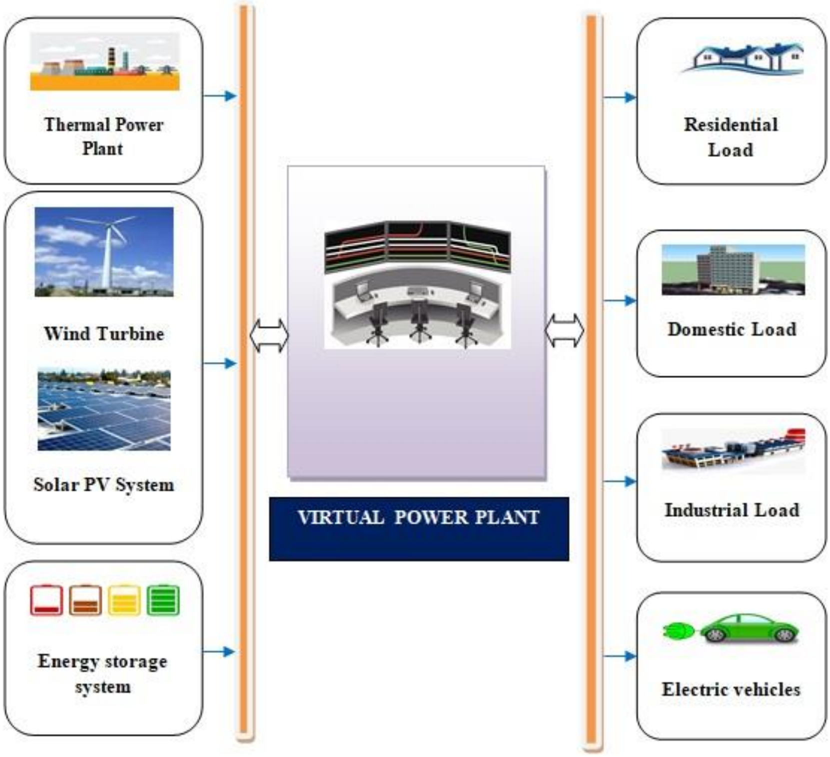

Fig. 1. General block diagram of virtual power plant.

3. Fractional Order PID Controller-Based VPP

Virtual Power Plant (VPP) is one of the developing ideas in power distribution systems to increase the participation of Renewable Energy Sources in the energy market. This work investigates the closed-loop response of Fractional Order Proportional Integral Derivative (FOPID) controlled VPP. The objective of the suggested system is to improve the dynamic response of closed-loop VPP by employing a controller. This controller is proposed to produce a faster response of VPP with lesser spikes in output voltage and power. The proposed model has been simulated with a Fractional Order Proportional Integral Derivative (FOPID) controller. Simulation performance is analysed and the results show an improved dynamic performance by employing the FOPID controller. The investigation indicates that FOPID controller-based VPP reduces the peak time, settling time, and low steady-state error in VPP. FOPID controller uses VPP and also improves the voltage, real power, and reactive power.

$$H_n(t) = (-1)^n e^{t^2} \frac{d^n}{dt^n} e^{-t^2} \tag{1}$$

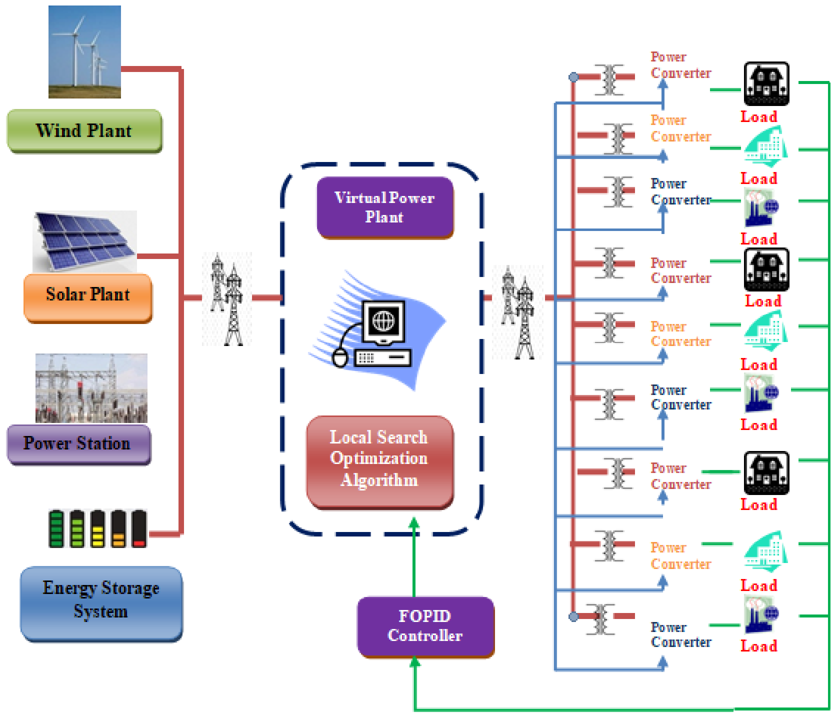

Fig. 2. Block diagram of FOPID-controlled virtual power plant.

A fractional order PID controller is applied to the Local search optimization (LSO) based VPP and their operation is represented as a block diagram in Fig. 2. A FOPID controller is required to minimize the voltage fluctuations in VPP. The proposed concept is applied to DER for optimal operation of energy storage devices and distribution loads using the appropriate power converters. The load voltage is tracked to determine the error and the error voltage compared to the reference voltage. The proposed controller is used to reduce the error in the closed-loop VPP system. The switching pulses for the power converter have been updated using the FOPID controller. This controller is also used to improve the small-scale stability of the VPP system. This work deals with the identification of a controller for VPP and the proposed FOPID controller is used to improve time domain responses.

3.1. *Virtual power plant with FOPID controller*

The simulation of FOPID controller-based VPP is discussed in this section. In the closed loop operation of the virtual power plant, the actual voltage behaviours are compared with reference by the controller to measure the error. The firing pulses are generated based on the error and given to the converter. By applying this concept, losses will be reduced in a virtual power plant. Figs. 3 and 4 show the phase and RMS voltage of VPP with the FOPID controller.

4. Proportional Resonant Controller-Based VPP

The proposed PR controller is used to improve the dynamic sensibility of the closed-loop VPP system. The Proportional Resonance (PR) controller-based VPP model has been simulated, and their result improves the dynamic performance of VPP. PR controller is more effective than the FOPID controller in terms of reducing peak times, settling times, and low steady-state errors. As compared to FOPID controllers, PR controllers employ VPP to enhance the profile of voltage, real power, and reactive power. The result shows that the PR controller produces better responses in VPP.

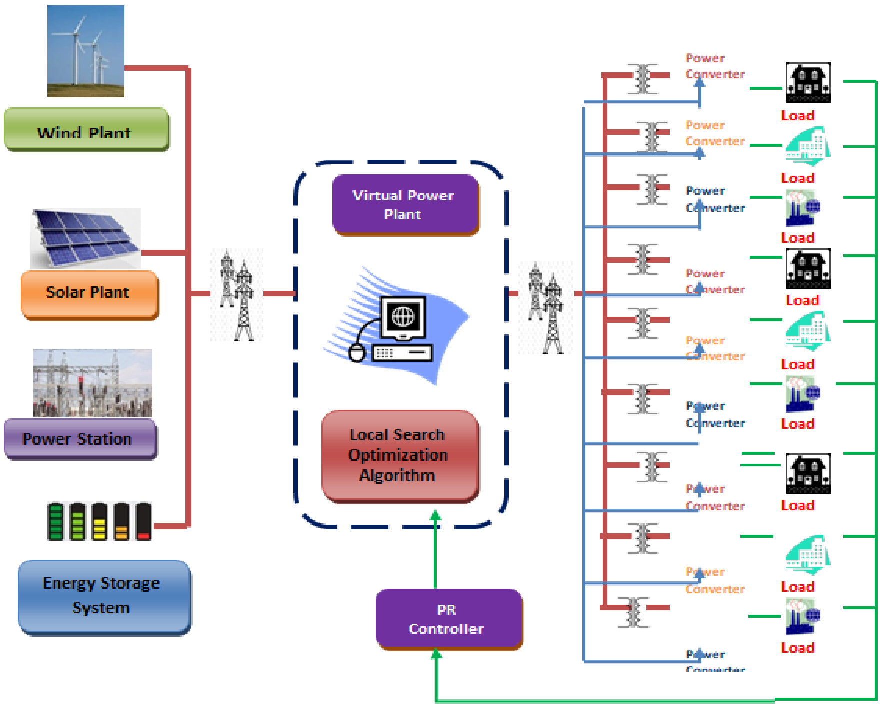

Fig. 3. Proportional resonant controller-based virtual power plant.

4.1. *Proportional resonant controller*

A proportional resonant controller is a transfer function-based closed-loop controller. As their name mentioned, proportional and resonant values are tuned independently based on reference behaviour. The block diagram of a proportionally controlled VPP is shown in Fig. 3. Power is delivered to the load from both traditional and ESE sources. The load voltage has been measured and contrasted with the reference voltage to ascertain the error. The error is handled by the PR controller to improve the overall response of the system. The pulse width of the boost converter is updated using the PR controller.

The transfer function of the proportional resonant controller is designed in the form of an equation as shown below. The transfer function of PRC is as follows,

$$G_C(sec) = K_p + \frac{2K_i sec}{sec^2 + \omega_0^2} \quad (2)$$

Where ω_0 is the target reference frequency and $s^2+\omega_0^2$ denotes infinite gain for reference frequency ω_0. This is used to solve the issues of damping resonant frequency in PR Controllers.

$$G_C(sec) = G_{Cp}(sec) + G_{Cr}(sec) = K_p + \frac{2K_i\omega_c sec}{sec^2+2\omega_c sec+\omega_0^2} \quad (3)$$

Where ω_c is the resonant frequency based on the resonant filter's breadth. The gain ω_0 is adjusted to be finite in the formula above, but it is changed sufficiently to lower the steady-state error. The bandwidth is increasing around ω_0 to increase the tolerance of frequency deviations.

5. Results and Discussion

PR controller applied virtual power plant is simulated with optimal allocation of solar and wind plants in the distribution network. PR controller is trained based on the error between actual and reference voltage. The reference value is taken from load characteristics to improve the transient response in the VPP system. Wind and solar plants are optimally connected to corresponding buses based on the local search optimization algorithm in VPP. The simulation of FOPID and PR controllers with VPP has been completed and their results were presented in the previous section. Time domain parameters of FOPID and PR controller are compared and their voltage, active, and reactive power are analyzed.

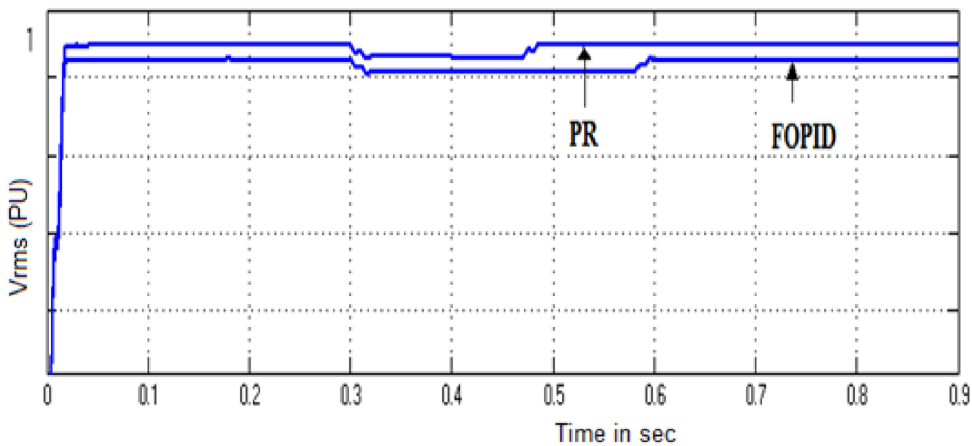

Fig. 4. RMS voltage with FOPID and PR controller.

5.1. *Voltage comparison*

Fig. 4 illustrates the RMS voltage comparison of the PR and FOPID controller in a virtual power plant. The FOPID controller produces a voltage of 8.2 kV at 0.02 sec, the voltage value is changed to 8.0 kV at 0.3 sec due to load change and DER performance. The rms voltage is 8.2 kV is obtained by tuning the parameters of the FOPID controller in VPP at 0.6 sec. Proportional resonant controller applied VPP produces the RMS voltage 8.4 kV at 0.018 sec and is reduced to 8.3 kV due to load characteristics at 0.3 sec. PR controller parameters are tuned to reduce the steady error in VPP and the actual value of 8.4 kV reached at 0.5 sec.

5.2. *Real power comparison*

The comparison of the real power of FOPID and PR controller in VPP is presented in the waveform of Fig. 5. The real power of the FOPID controller begins from 0 to 0.88 MW at 0.2 sec. The real power value decreases to 0.86 MW at 0.3 sec with respect to change of load and DER behaviors. The parameters of FOPID controller Kp, Ki, and Kd are selected properly for the power losses in VPP. The real power returns to the original value of 0.88 MW at 0.6 sec after the operation of the FOPID controller. The PR control-based VPP produces a real power of 0.93 MW at 0.018 sec. Due to load disturbance at 0.3 sec, the real power is reduced to 0.9 MW. PR controller is used to reduce the steady-state error; the real power value is updated to 0.93 MW with a fast response at 0.5 sec after the performance of the PR controller.

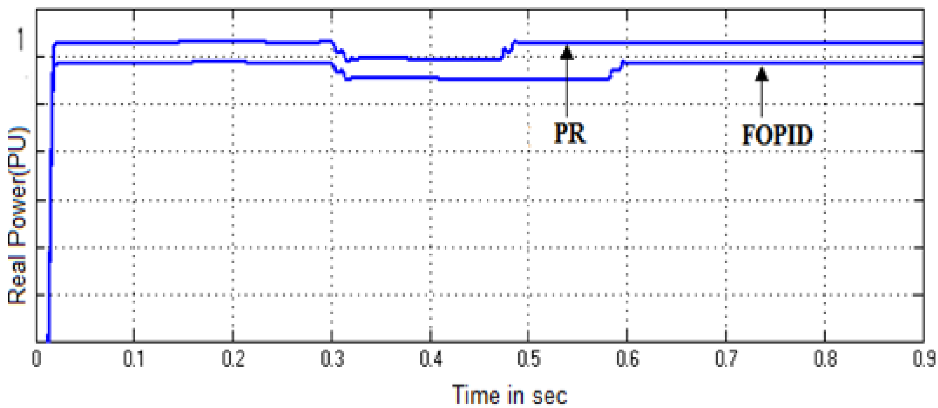

Fig. 5. Real power with FOPID and P.R controller.

5.3. *Reactive power comparison*

The reactive power of VPP with the FOPID controller is shown in Fig. 6. Initially, the reactive power value is zero and it rises to 0.265 MVAR at 0.016 sec based on the allocation of DER in the distribution side. The load and DER values are changed at 0.3 sec and reactive power is reduced from 0.265 MVAR to 0.255 MVAR. Fractional values are opted to tune the parameters in the FOPID controller, reactive power value is reassigned to 0.265 MVAR at 0.6 sec. PR controller-based virtual power plant produces better responses in real power compared to the FOPID controller. At the initial stage, the reactive power value is zero and rises to 0.285 MVAR at the time of 0.014 sec. Due to load and DER behavior change at 0.3 sec, the reactive power has reduced to 0.275 MVAR at a time is 0.3 sec. PR controller trained and the reactive power returned to the value of 0.285 MVAR at 0.5 sec. PR controller reduces the steady error compared to the FOPID controller.

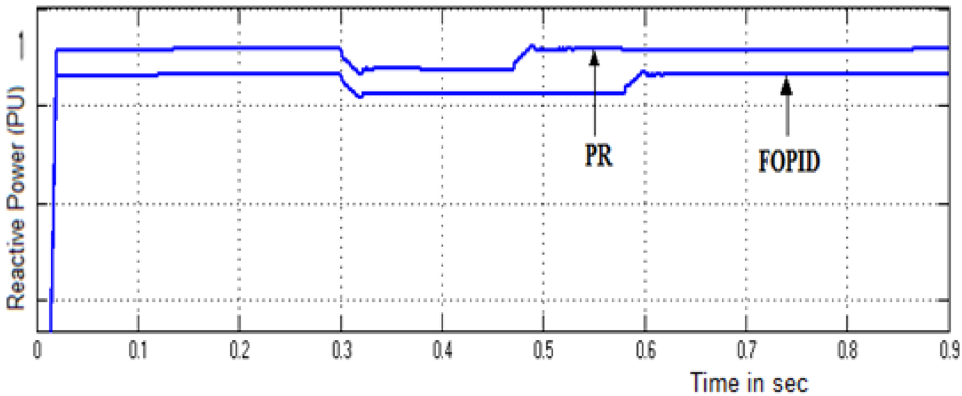

Fig. 6. Reactive power with FOPID and P.R controller.

5.4. *Comparison of time domain parameters*

The comparison of time domain parameters with FOPID and PR controllers is given in Table 1. The rise time is reduced from 0.318 sec to 0.315 sec; the peak time is reduced from 0.52 to 0.44 sec; the settling time is reduced from 0.60 to 0.49 sec and the steady state error is reduced from 3.21 to 2.78 V by replacing FOPID controller with PR controller. Dynamic response is also improved by using a PR controller. A comparison of FOPID and PR-controller is presented in Fig. 7.

Table 1. Comparison of time domain parameters in FOPID and PR controller.

Performance analysis	Rising time (sec)	Settling time (sec)	Peak time (sec)	Steady-state error (V)
Without controller	0.325	0.72	1.25	5.35
FOPID Controller	0.318	0.60	0.52	3.21
Performance improvement in FOPID controller	2.16 %	16.67 %	58.4 %	40 %
PR controller	0.315	0.49	0.44	2.78
Performance improvement in PR controller	3.08 %	31.95 %	64.8 %	48.04 %

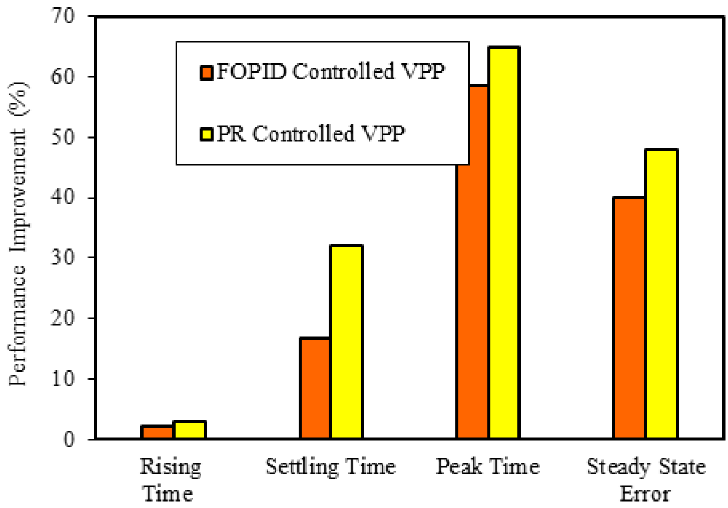

Fig. 7. Comparison of time domain parameters of FOPID and PR controller in VPP.

6. Conclusion

This research work implemented two controllers for the VPP to enhance stability. FOPID and PR-controlled VPP system is modelled, and their performance has been analysed. The simulation results of the closed-loop VPP System with FOPID and PR controller are compared. By representing a PR controller for the proposed VPP, the steady-state error is decreased from 3.21 to 2.78 in phase voltage, and the settling time is decreased from 0.60 to 0.49 sec. The performance of the implemented Proportional Resonant (PR) controlled virtual power plant has been compared to that of the FOPID-based virtual power plant. The dynamic response of the rising time has been improved by 3.08 %, the settling time by 31.95 %, the peak time by 64.08 %, and the steady state response by 48.04 % with the implementation of the PR-controlled VPP system. In the VPP system, the PR controller outperforms the controller that handles FOPID results. The response of the PR controller is superior compared with FOPID in VPP. The advantages of the proposed system are high reliability and improved response. The effectiveness of the VPP system has been improved using PR. The proposed research work is to identify a closed-loop VPP system with enhanced stability of PRC. The investigations reveal that PR controller-based VPP shows better performance than FOPID. It can be shown that the time response with the PR controller is superior to the controlled VPP system.

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