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Research Article

Virtual oscillator with delayed feedback for transient mitigation in inverter-based islanded microgrids

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Abstract. In recent years, the conventional control schemes for renewable energy-based inverter-dominated microgrids have been expeditiously replaced by Virtual Oscillator-based Control (VOC). The method of VOC ensures fast synchronisation and efficient load-sharing capabilities in inverter-based renewable energy systems. This work evaluates the effectiveness of VOC-based inverters in mitigating the transient dynamics of power system parameters like voltage, frequency and current under different types of switching events involving active and reactive load combinations. Further, to enhance the control efficiency of VOC under such load-switching scenarios a modified form of VOC is proposed utilizing the ability of the feedback mechanism to strengthen the state space trajectory of dynamical systems. In the proposed method, the control oscillator of conventional VOC driven by the inverter current is modified by providing a feedback signal in the form of an integral function of the error between the drive oscillator and the trajectory of the inverter output. The efficiencies of different forms of feedback are quantified in terms of percentage deviation in power system parameters as well as THD. The proposed feedback strategy can improve the control performance by bringing down the voltage deviation from 57% in conventional VOC to around 4%. Likewise, the frequency deviation is brought down to 0.14% from 19.26%. These advantages are achieved without any significant adverse impact on the THD. The proposed approach can be utilized in multi-inverter-based systems serving sensitive loads in microgrids.

Keywords: Delayed feedback, Islanded microgrids, Transient dynamics, Van der Pol (VdP) oscillator, Virtual Oscillator Control (VOC)



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1. Introduction

The continuously growing demand for electrical energy as well as environmental concerns regarding conventional large-scale fossil fuel-based generation systems have led to a surge in the development of relatively smaller systems comprising environment-friendly generation relying on renewable energy sources (Shahgholian 2021). A group of such distributed generation units connected to a standard utility through power electronic interfaces form a microgrid (Shayeghi *et al.* 2021).

Figure 1 shows a renewable energy-based microgrid consisting of solar array, wind farm and energy storage systems. Such microgrids have eased the burden on the vast utility grid in terms of reduced distribution losses as well as environmental impacts and have contributed significantly to improvements in power quality and reliability (Khetrapal et al. 2020). The DC power generated from these sources is converted into AC supply by inverters and the design of current controllers determines the quality of current delivered by such interfacing units (Muhtadi et al. 2021). However, the fluctuating nature of renewable resources together with varying load demand impact the voltage and frequency stability and thereby impose critically strong operational control requirements on the microgrid (Razmi et al. 2022). Designing effective control strategies to ensure smooth functioning during grid-tied and islanded modes as well as during mode transitions has become the key element

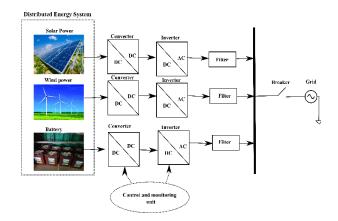


Fig. 1 Distributed energy based microgrid

of development procedure for Distributed Energy Resource (DER) based systems (Reddy et al. 2019; Jalil et al. 2023). During the islanded mode of operation, microgrids are required to function as autonomous power systems capable of maintaining stability and serving local loads, facilitating efficient generation and distribution of electric power (Moghaddam et al. 2021). Hence, optimal control strategies for islanded mode demand special consideration due to the absence of grid support in

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terms of voltage and frequency references (Qachchachi et al. 2020)

The operation of islanded microgrids can be significantly affected by faults or the switching of various types of loads. A variety of control schemes have been proposed in the literature to address these phenomena (Naderipour et al. 2023; Rizvi et al. 2023; Lin et al. 2020). Major forms of control are droop and resonant controllers. Droop control relies on real and reactive power measurements, for frequency and voltage regulation, and advanced architectures for the same have become popular in recent years (Ujikrismanto et al. 2018; Leea et al. 2016; Shi et al. 2022). The addition of a secondary level of Proportional Resonant (PR) controllers along with the primary droop controllers has been proven superior in the grid-connected mode in terms of steady-state tracking error and disturbance rejection. Comparative analysis of the performance of resonant controllers and optimised PI controllers has provided enhanced performance (Hlali et al. 2019; Nair et al. 2023). The general limitation of these approaches is the requirement of complex control loops which require careful tuning in terms of stability and system parameter limits (Jiang et al. 2020; Roselyn et al. 2020). To increase the effectiveness of droop control, virtual impedance scheme has been extensively studied and implemented across the literature for achieving efficient power sharing and harmonic mitigation (Astrada et al. 2022; Wang et al. 2023). An equally competent control strategy for microgrid operation mimics the inertial response of a generator using a virtual synchronous machine (VSM) and has been proven equivalent to droop control under different operation conditions (Liu et al. 2018). The requirement of complex control loops and mathematical transformations and dependence on DG feeder impedance are major limitations of these approaches as well (Unamuno et al. 2017).

A novel concept of Virtual Oscillator Control (VOC) based on dynamical systems theory is a recent major development in inverter control systems. Herein the inverter and a non-linear oscillator with a stable limit cycle trajectory are coupled to each other, thereby achieving efficiency and additional functionalities with minimal design complexity (Aghdam et al. 2022; Costa et al. 2021). Synchronisation of coupled oscillators is the key element of the VOC approach that provides sustained oscillations in the inverter output(Joshi et al. 2016). VOC is a time-domain approach which depends on instantaneous inverter current measurements, thus ensuring a faster response as well as synchronization between inverters (Sinha et al. 2015; Gurugubelli et al. 2022). Various topologies of VOC have been investigated for different modes of operations of microgrids in terms of power-sharing and control of frequency and voltage (Johnson et al. 2014; Mohammed et al. 2023; Han et al. 2023). The application of VOC in hierarchical control of inverters in both grid-connected and islanded modes of operation has been experimentally verified for varied purposes of regulation as well as power sharing (Raisz et al. 2019). VOC performs efficiently in mode transitions as well, with faster response time compared to droop as well as other control methods (Fan et al. 2022; Alghambi et al. 2022).

The main focus of VOC based control of microgrids has been synchronisation and power-sharing and has been widely reported for resistive load changes (Shi *et al.* 2020; Gurugubelli *et al.* 2021). Microgrid which is an interface to various non-linear elements, the effect of switching events in the presence of such loads is of utmost relevance, especially in islanded autonomous mode. The behaviour of such microgrids with nonlinear elements under transient events using established droop and resonant controller has been investigated in (Rashwan *et al.* 2023; Valedsaravi *et al.* 2023), but the performance of VOC-based control during the switching of such loads is barely

investigated. During load-switching events, voltage transients penetrate the electrical system and their unpredictable nature and extremely short-duration of incidences makes them hard to be captured by conventional analysis methods (Pannila et al. 2020). Voltage transients are generally characterized by highmagnitude peaks of very short duration with fast-rising edges caused by switching in capacitor banks and microgrids, or transformer tap changes or arcing due to malfunctions (IEEE Standard 1159-2019, Bollen et al. 2005). Power electronic devices which are commonly used in microgrids and renewable energy systems can also produce transient spikes. Abrupt changes in current demand or load, particularly from capacitor bank switching in industrial facilities, significantly contribute to transient occurrence. With durations lasting microseconds to milliseconds (ANSI/IEEE C62.41-1991) and voltage spikes in magnitude ranging to several multiples of nominal voltage, such transients often pose significant risk to sensitive equipment connected to the systems as well as to power quality and thereby system reliability, thus necessitating appropriate mitigation methods which can safeguard connected equipment and maintain power system reliability(Sepasi et al. 2023; Rodrigues et al. 2023). Hence, this work is undertaken to investigate the dynamic evolution of microgrids with reactive loads under transient events and propose a computationally simple strategy for VOC which can significantly reduce the spike levels of such transients.

In dynamical systems theory, the feedback mechanism has been the strongest and dominant approach for controlling trajectories of chaotic systems (Xu et al.2021; Watanabe et al. 2023). Considering the efficiency of the feedback mechanism in controlling unstable periodic orbits of dynamical systems, it is hypothesised that an appropriate feedback strategy can effectively suppress the disturbances generated during transient events in microgrids involving combinations of reactive elements. Self-feedback in a system provides flexibility in the output produced by systems in terms of diverse nature and stabilisation (Lazarus et al. 2016; Hakimi et al. 2021). Highly periodic stable waveforms can be obtained by adjusting the delay and the feedback gain even in chaotic systems (Peng et al. 2020; Kashchenko 2023). Time-delayed feedback has been proven effective in stabilising unstable orbits and is achieved with no prior knowledge of the periodic orbits (Pyragus 2006; Pyragus et al. 2018). The basic principle of this approach is to control the system dynamics through a small perturbation which is proportional to the difference between the present state of the system and the state at a delay of one period. This approach helps to attain a periodic trajectory by means of negligible perturbations applied in the form of diffusive coupling (Montenbruck et al.2015; Lautenbacher et al.2024) which dies down when the two trajectories converge.

Conventional VOC and all its related forms of control reported to date are designed by taking specific advantage of the dynamical properties of the mutual coupling between the inverter and the reference oscillator. Specific advantages like the ease of implementation and fast response of the novel simple method of VOC over other control methods are favourable by-products of mutual coupling between non-linear dynamical systems. Improved performance methods (Guo et al. 2023; Opila et al. 2019) discuss VOC based on different oscillator forms, utilisation of additional control loops and communication layers for addressing load changes involving resistive and nonlinear loads, without much focus on utility for microgrids with reactive elements. Considering the inherent feature of stabilisation of unstable periodic orbits, of time-delayed feedback, it is hypothesised that appropriately modifying the mutual coupling between the inverter-VOC system by incorporating such delayed feedback can efficiently handle such

transient events in microgrid with reactive elements. The objective of this work is to implement the above approach to achieve better control over the dynamics of microgrids during transients under different load conditions. Fractional error feedback, Error Function (ERF) feedback and Proportional Integral (PI) feedback have been extensively proven efficient in handling disturbances in a variety of systems with various applications (Alotaibi et al. 2021; Howard et al. 2022; Aguilar-López et al. 2013). The efficiency of different configurations of delayed modes such as fractional error, ERF and PI forms of feedback in overcoming the effect of transient events and thereby achieving efficient control are investigated. A comparative analysis of these methods among themselves as well as with the conventional VOC form is also presented. The performance evaluation is carried out in terms of its effect on different power system parameters of voltage, current, frequency, and active and reactive powers.

2. Method

2.1 System description

Van der Pol (VdP) oscillators have predominated the VOC owing to their merits regarding ease of implementation and robust dynamics. A Van der Pol oscillator consists of a) an inductor and capacitor which form the oscillator circuit b) a conductance element with a negative magnitude c) a voltage-dependent current source which varies with cubic voltage.VdP dynamics in terms of oscillator capacitor voltages v and inductor currents i_L as in (Johnson $et\ al.\ 2016$) are:

$$L\frac{di_L}{dt} = \frac{v_{vdp}}{k_v} \tag{1}$$

$$C\frac{dv_{vdp}}{dt} = -\alpha v_{vdp}^3 + \sigma v_{vdp} - k_v i_L - k_v k_i i$$
 (2)

where α is the coefficient of the cubic current source, σ denotes conductance, k_v and k_l represent voltage and current scaling factors and L and C are the harmonic oscillator inductance and capacitance respectively. The voltage and current scaling factors are chosen based on the inverter's rated power and open circuit voltage (Johnson *et al.* 2016).

Figure 2 shows the VdP with feedback scheme with the oscillator elements R, L and C and the scaling factors. To implement the feedback scheme, the output terminal voltage of the inverter is sensed and a feedback current is fed into the VdP in the form of a function that is proportional to the instantaneous difference between the inverter voltage ($V_{inverter}$) and scaled output of VdP (V_{vdp}) along with the inverter current drive i.

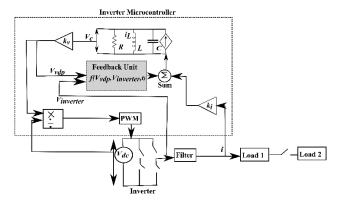


Fig. 2 Representation of proposed VdP with feedback for inverter

Table 1System description

Description	Value
Inverter DC link voltage	180 V
Nominal system frequency	$2*\pi*60$ rad/sec
Harmonic oscillator capacitance(C)	0.18 F
Harmonic oscillator inductance (L)	3.99x10 ⁻⁵ H
Conductance(σ)	6.09 Ω ⁻¹
Voltage Scaling Factor (k_{ν})	178 V/V
Current scaling factor (k_i)	0.15 A/A
Base RL load	R=20 Ω, L= 0.1 H
RLC load	R= 40 Ω , L= 0.2 H, C= 1 μ F

The system specifications of the microgrid and VOC parameters have been chosen as per the design strategy in (Johnson *et al.* 2016) and tabulated in Table 1.

2.2 Proposed scheme

With feedback, the equation Eq. (2) governing dynamics becomes as under:

$$C\frac{dv_{vdp}}{dt} = -\alpha v_{vdp}^3 + \sigma v_{vdp} - k_v i_L - k_v (k_l i + r I_{fb})$$
 (3)

Where r is the feedback fraction,

 $I_{fb} = function(v_{vdp}, v_{inverter}, t)$ is the feedback current and the function forms used are:

- Error feedback $\in = K_e(v_{vdp}(t) v_{inverter}(t))$ (4)
- Error Function feedback ERF(\in) = $\frac{2}{\sqrt{\pi}} \int_0^{\epsilon} e^{-t^2} dt$ (5)
- PI function feedback given by $H(\in) = K_p \epsilon + K_i \int \epsilon \, dt$ (6)

where K_e is the feedback fraction of error feedback whereas K_p and K_i are the PI feedback coefficients. All these forms are based on the concept of strengthening the coupling between VdP and inverter by means of providing a feedback as a function of fractional differences between reference VdP voltage and inverter output voltage. A simple error feedback as well as two integral forms, ERF and PI, are investigated. All three feedback forms are designed using the error between the outputs of the VdP and the inverter. The optimal value of feedback fraction is designed by conventional manual tuning of the parameters as follows. In the case of a simple error feedback, initially, the proportional fraction is set to zero and further slowly increased in small steps observing the corresponding changes in output error. Once the output error is found to decrease, the corresponding value of proportional fraction is noted and the procedure is continued until the error reaches the lowest possible value and starts to increase with further increase in proportional fraction. The value of the proportional fraction corresponding to the lowest possible error value is chosen for all further dynamical analyses with delayed error feedback. In the case of integral feedback form, the ERF function of the fractional error between VdP and inverter outputs is provided as the feedback signal. Here again, the same procedure is followed for estimating the optimal value of feedback fraction in the ERF function. For PI feedback form, the conventional tuning procedure is followed. The tuning procedure is started by setting the proportional term K_p and integral term K_i to zero. Further, the proportional term K_p is increased in small steps similar to the procedure followed in previous cases. Once the optimal value of K_p is identified, the integral fraction K_i is increased, observing the corresponding changes in the output

error. Again the optimal value of K_i is identified from the ranges for which the error decreases to the lowest possible value and increases with further increase in K_i . These values of K_p and K_i are used in further dynamical analyses.

3. Results and discussion

The performance is evaluated for three forms of feedback functions a) fraction of error feedback b) ERF function of error c) PI of error for the load scenarios of i) base load and ii) a combination of R, L and C load (RLC) switching. A standalone microgrid is investigated with reactive load switching using conventional VOC control as well as proposed VOC with feedback forms and numerically investigated using MATLAB simulation as per parameters in Table 1. Here the results of the performance evaluation of the proposed approach with delayed feedback mode under different load change conditions are presented. Performance comparison is carried out in terms of the dynamics of the voltage, current and frequency at PCC (Point of Common Coupling), active and reactive powers, for each of these cases.

All VOC approaches proposed to date, employ nonlinear oscillators with a current drive acquired from the inverter output terminal. Though it is proven to be better in performance for synchronization of inverters and power-sharing, certain limitations concerning its performance under transient dynamic scenarios like different types of load switching have been observed. To overcome these limitations, we propose the use of delayed feedback with the view of stabilizing the limit cycle of the VdP oscillator which is supposed to drive the inverter output through the mode of coupling between them. The performance of the VdP oscillator with feedback is compared with the conventional case of VdP without feedback.

3.1 Conventional VdP without feedback

To analyse the dynamics of the inverter with the conventional form of VOC as the control scheme under different transient switching events, an inverter with a base load and VdP as the controlled oscillator is simulated for different types of load switching.

Figure 3 (a-c) shows the dynamics under RLC load switching compared with the base load. Initially, the system starts with the base load and the additional load is switched at 3s. It can be observed that the PCC voltage in Fig. 3(a) shoots up by 56.62% in the case of RLC load switching which is much higher than the allowed limits of +10% as per IEEE 1547 limits (Rebollal *et al.* 2021), as in Table 3. Similarly, the surge in current during load

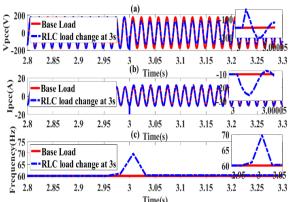


Fig. 3 Steady-state and dynamic evolution of PCC (a) voltage (b) load current and (c) frequency for inverter controlled with conventional VdP without feedback for the two load cases

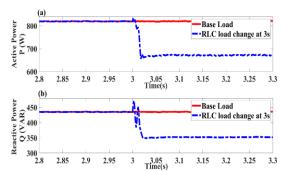


Fig. 4 Steady-state and dynamic evolution of (a) active power and (b) reactive power for inverter controlled with conventional VdP without feedback for the two load cases

switching as per Fig. 3(b) is about 155.62% and Fig. 3(c) shows that there is a substantial difference in frequency in the range of 19.26% in the case of RLC load switching. In general, it can be observed that the transient dynamics are detrimental in RLC load switching where the shoot in the PCC voltage and current is far crossing the allowed limits (Rebollal *et al.* 2021). Even in the case of frequency, the fluctuations are above these limits. Though the system regains the steady-state dynamics within a very short time, the instantaneous overshoot at switching is considerably high to enable the tripping.

Figure 4 (a) and (b) show the variation in active and reactive power for VdP-controlled RLC load change compared with the base load condition. These observations call for the need for stable VdP control under dynamic scenarios, especially in the context of microgrid scenarios. Hence further investigations are carried out on the performance of different modes of operation of the nonlinear oscillator (VdP oscillator) that can enhance the robustness of its limit cycle against such disturbances. Considering the relevance of feedback in the stabilization of oscillator dynamics, delayed feedback modes are investigated and performance evaluation is carried out to identify the better operating regime under changing load conditions.

3.2 Delayed feedback to VdP

The performance of VOC with delayed feedback of different forms is investigated in comparison with that of conventional VOC under two cases. Case 1: Steady state base load condition and Case 2: dynamic scenario of RLC load switching. The evaluation is done with a comparison of voltage, current, frequency, and active and reactive powers for all forms in both cases.

Case 1: Base load

Figure 5 shows the evolution of PCC voltage and current for error, ERF and PI modes of delayed feedback given to VdP. As seen from Figure 5(a) and (c), error and ERF forms of feedback show longer settling times of 1.15 and 1.06 s in PCC voltage respectively compared to no feedback settling time of 1.022 s. This is just 12.7% & 4% more than the settling time of VdP without feedback. From Figure 5(e), it can be seen that PI delayed feedback with a settling time of 1.01 s in PCC voltage, performs better in terms of settling time suggesting faster convergence of the VdP trajectory to its limit cycle. The integral term in the PI form strongly drives the trajectory to reference thus achieving better convergence. Even in the case of ERF feedback, the integral term is found to help with trajectory convergence. Figure 5 (c) and (e) thus indicate the effectiveness

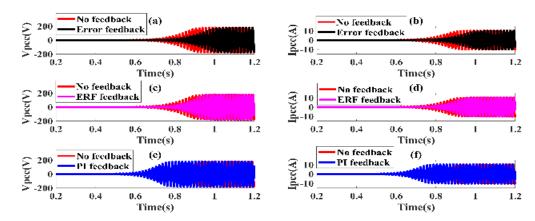


Fig. 5 Steady-state evolution of PCC voltage and current for VdP with delayed feedback, of the forms error feedback, ERF feedback and PI feedback, compared to VdP without feedback

Table 2Comparison of THD and frequency for VOC implemented using VdP with delayed feedback to that of conventional VOC

	Comparison of THD and frequency before, during and after RLC load switching					
Feedback form		efore RLC switching At R (Base load)		witching	ng After RLC switching	
	THD	f(Hz)	THD	f(Hz)	THD	f(Hz)
No feedback (Conventional)	2.46	60.07	2.93	71.65	3.16	60.25
Fraction of error	2.07	60.53	2.58	63.8	2.74	60.77
ERF of error	2.92	60.36	3.32	60.49	3.60	60.44
PI of error	2.92	60.36	3.27	60.45	3.60	60.43

of adding an integral term to the feedback signal in achieving the required response.

Figure 5 (b), (d) and (f) show the evolution of PCC current for error, ERF and PI modes of delayed feedback given to VdP compared to VdP without feedback respectively. From figures 5 (b), (d) and (f), it can be seen that compared to the settling time of 0.97 s of no feedback VdP, output current settling times of ERF and PI delayed feedback forms are 0.98 s and 1.0 s r espectively whereas error delayed feedback exhibits a settling time of 0.92 s.

Figure 6 shows the steady state evolution of PCC frequency in the case of error, ERF and PI forms of delayed feedback respectively. It can be seen that in the case of frequency, for base load, all three forms are found to perform better compared to VdP without feedback. The settling times of these forms are

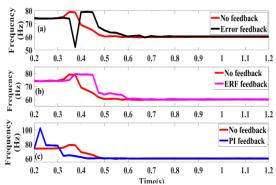


Fig. 6 Steady-state evolution of PCC frequency for VdP with delayed feedback, of the forms error feedback, ERF feedback and PI feedback, compared to VdP without feedback

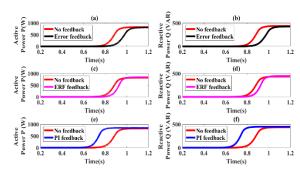


Fig. 7 Steady-state evolution of active and reactive powers for VdP with delayed feedback, of the forms error feedback, ERF feedback and PI feedback, compared to VdP without feedback

0.5~s for error and PI and 0.52~s for ERF form. These values are comparable to the settling time of 0.498~s of no feedback VdP.

Table 2 shows the THD percentage and frequency of conventional and delayed feedback forms of VdP before, during and after RLC load switching. From Table 2, it can be observed that with base load, the THD value for error feedback is 2.07% and 2.92% for both ERF and PI feedback forms compared to no feedback THD of 2.46 %. This indicates that the differences are negligible and maintained below 3% which is well within the IEEE- 519 stipulated margin for THD of less than 8%

Figure 7 shows active and reactive power output for the different error, ERF and PI modes of delayed feedback modes. Herein it can be observed that the shortest settling time of 0.81 s is obtained with PI delayed feedback. ERF and error feedbacks are found to take longer times of 1 and 1.23 s for settling. These two forms of feedback are found to be relatively compromised to conventional VdP without feedback, though the difference is

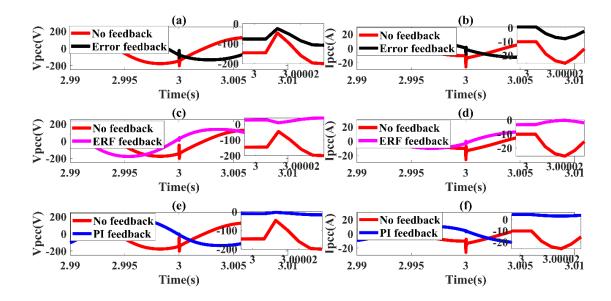


Fig. 8 Dynamic evolution of PCC voltage and current for VdP with delayed feedback, of the forms error feedback, ERF feedback and PI feedback, compared to VdP without feedback

Table 3Comparison of percentage deviation in power system parameters for VOC implemented using VdP with delayed feedback with that of conventional VOC during transient

	Change in power system parameters during RLC load switching					
Feedback form	% change in voltage	% change in current	% change in frequency			
Vo feedback conventional)	56.62*	155.62	19.26*			
Fraction of error	29.67*	84.55	5.4*			
ERF of error	9.91	27.07	0.2			
PI of error	3.74	11.56	0.14			

^{*-}overshoot in PCC system parameters as per IEEE 1547 standards in (Rebollal et al. 2021)

significantly small. A similar advantage with PI feedback as observed in the dynamics of PCC voltage, current and frequency has been found in active and reactive power as well compared to conventional VdP.

Case 2: RLC load switching

Here the microgrid system is subjected to RLC load switching at 3s and performance evaluation is carried out for conventional VOC and the proposed approach of VdP with delayed feedback. For this purpose, the percentage deviation in power system parameters is evaluated as follows:

% change =
$$\frac{(Value \ at \ switching - Value \ prior \ to \ switching)}{Peak \ value} \times 100\%$$
 (7)

The values of percentage changes for conventional VOC and proposed forms of delayed feedback in power system parameters for the different feedback forms are calculated as per (7) and given in Table 3.

Figure 8 shows the dynamic evolution of PCC voltage and current for VdP with delayed feedback for error, ERF and PI modes respectively along with that of no feedback for RLC loadswitching. As seen from 8 (a), (c) and (e), compared to the 56.62% surge in voltage in the case of VdP without feedback,

error, ERF and PI feedbacks provide much better results with a decrease in the surge to 29.67 %, 9.91 % and 3.74 % respectively as seen from Table 3. With the error feedback, wherein a fraction of the error between VdP and inverter voltages is fed back to the VdP, the surge in voltage is effectively reduced to half of that in the case of conventional VdP. The percentage change is found to be lowered by a factor of around 6 and 15 for ERF and PI feedbacks respectively. With delayed feedback of errors, the system shows a tendency to strengthen the trajectory. This is further enhanced by the addition of an integral term with PI and ERF forms, thereby maintaining the system trajectory with minimal deviation. This can thus provide robust dynamics to the power system parameters keeping them well within the allowed IEEE 1547 margin of -30% and +10% (Rebollal *et al.*2021) even during transient switching events.

From Figures 8 (b), (d) and (f), it can be observed that the percentage change in current, according to equation (7), for VdP without feedback is 155.62%. As seen in Table 3, providing delayed error feedback is found to bring this down to a value of 84.55 % for error feedback whereas the inclusion of integral term significantly reduces the changes to 27.07% and 11.56% with ERF feedback and PI feedback respectively.

Figure 9 (a-c) shows the dynamic evolution of PCC frequency for error, ERF and PI delayed feedback VdP along

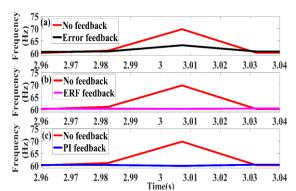


Fig. 9 Dynamic evolution of PCC frequency for VdP with delayed feedback, of the forms (a) error feedback (b) ERF feedback (c) PI feedback, compared to VdP without feedback

with that of no feedback for RLC load switching. From this figure as well as the frequency and THD values given in Table 2, it can be observed that during the load-switching event, the frequency undergoes a drastic shift to reach a value of 71.65 Hz for conventional VOC employing VdP without any feedback whereas with delayed feedback of fractional error, the frequency shifts to 63.8 Hz. Both of them are higher than the IEEE 1547 standards of -1.5 Hz and + 1.2 Hz (Rebollal et al.2021). However, with the inclusion of integral error to the feedback as employed in ERF and PI forms, frequency shifts to only 60.49 Hz and 60.45 Hz during the transient event, which demonstrates the robustness of the system trajectory towards disturbances. This shows the effectiveness of employing an appropriate feedback form to enhance the sturdiness of the power system with the proposed VOC form. Again from Table 2, it can be observed that the THD percentages for all these proposed forms are within the IEEE 519 limits of 8 %. Even during the switching instant as well as with the newly introduced RLC load, the maximum THD value is only 3.6 % which is observed for both the ERF and PI feedback forms. This value is comparable to the corresponding value of 3.16 % for conventional VOC with RLC load. Though the integral feedback forms induce a small increase in THD, it comes with the advantage of keeping the power system parameters within the

IEEE 1547 stipulated values. Notably, these integral feedback forms effectively provide strength to the system against disturbances without any significant impact on THD.

Table 3 shows the comparison of percentage deviation in power system parameters for VOC implemented using VdP with delayed feedback with conventional VOC during transient. The percentage deviation in frequency during transient, is 19.26 % for conventional VOC, whereas for error feedback it is 5.4 %. This deviation is reduced to 0.2% and 0.14% for the two integral feedback forms, namely ERF and PI respectively. The THD values during the switching instant for error-delayed feedback are about 2.58 % and for ERF and PI, it is about 3.32 % and 3.27 % respectively which is about 0.39 %- 0.34% higher than the value of 2.93 % for VdP without feedback as seen from Table 2. However, all these values are within the IEEE 519 standard for THD limit of 8%.

Figure 10 shows the evolution of active and reactive power for error, ERF and PI feedback modes during the switching of RLC load in 3 s. It can be observed that there is a shift in these values and the shift in reactive power is higher than active power. The swing in both active and reactive powers is observed to settle down within a considerably short duration of 0.02 s. The phenomenon is consistent with the dynamics observed in PCC voltage and output current.

The above results evidence the advantage of including an appropriate delayed feedback scheme in providing robustness to the system trajectory towards unforeseen disturbances, with minimal invasion on THD values. Though the THD values are slightly higher for delayed feedback forms of ERF and PI with a difference of about 0.39 % and 0.34 % from VdP without feedback at the RLC load switching instant, they are all still within the IEEE 519 limits on THD of less than 8%. Harmonic Distortion (THD) calculation based on Fourier analysis typically operate on timescales of at least 1 second, capturing harmonic content over longer periods. These methods may not effectively capture transient events which occur on much shorter timescales of order microseconds to milliseconds. Transients despite not being reflected in traditional THD analysis can still cause significant harm to connected equipment and power system relaiability. The proposed method is found to be efficient in handling transient dynamics under dynamic load conditions, by bringing down the

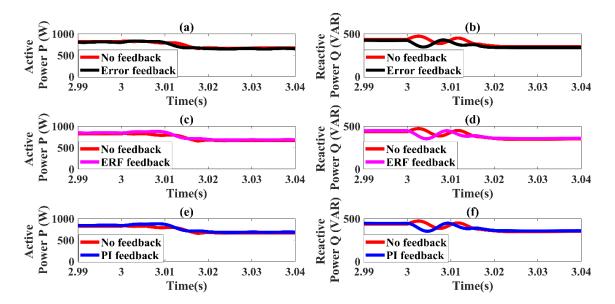


Fig. 10 Dynamic evolution of active and reactive powers for VdP with delayed feedback, of the forms error feedback ERF feedback PI feedback, compared to VdP without feedback

percentage change in the system voltage and frequency within the IEEE 1547 standards.

As seen from Table 3, the improvement in percentage voltage regulation during switching with delayed error, ERF and PI forms are comparable or even more efficient compared to other methods employing added components like Static Var Compensator and Supercapacitor (Awad et al. 2020) where the percentage improvement achieved was only about 70.28%. and 75.81% as achieved with the control strategy (PavanKumar et al.2021). In addition to this, the proposed scheme commensurates voltage and frequency regulation values with control schemes involving metaheuristic algorithms for autonomous microgrids (Qazi et al. 2018). Moreover, the settling time achieved with the proposed delayed feedback scheme is comparable to the enhanced control for resistive loads achieved with the fuzzy logic approach reported in a similar investigation (Lasabi et al. 2022). From the results of the current investigation, it can be deduced that the proposed method with delayed feedback can provide improved voltage and frequency regulation, without much complicated strategies involving physical or computational complexity.

4. Conclusion

A modified form of VOC is introduced to enhance the robustness of the state space trajectory of power inverters and to improve the control efficiency under transient load switching scenarios. With conventional VOC-based control, the transient disturbances become significantly higher than the IEEE stipulated limits during the switching of RLC loads, thus necessitating performance enhancement of the same. For this purpose, a delayed feedback scheme which is a proven approach in stabilization of system trajectories in dynamical systems theory is proposed. The efficiency of various forms of feedback in controlling the system dynamics and thereby suppressing the transients is investigated under load-switching conditions involving reactive elements. With simple fractional error feedback, the voltage deviation is reduced to around 30% from 57% and the frequency deviation to 5% from 19%. However, with this simple feedback form, the values of voltage and frequency could not be brought down to the stipulated IEEE standards. Further reduction in the voltage deviation is achieved by adopting integral functions of the error namely ERF and PI forms of feedback. With ERF feedback, the voltage disturbance values are reduced to about 10% and 4% with PI feedback. Moreover, these feedback forms are also found to be effective in lowering the frequency deviation values to 0.2 % and 0.14% respectively, thereby limiting the parameters well within the IEEE standards. These advantages are obtained without any deleterious effect on THD. Thus the proposed feedback approach can provide a significant reduction in power system transients maintaining the THD values well within the permissible limits of IEEE standards.

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