Transient Mitigation in Islanded Microgrid with Modified Virtual Oscillator Control

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Abstract- Virtual Oscillator Control is a modern inverter control scheme for grid-forming inverters with specific advantages of high dynamic response and implementation simplicity, provided by its nonlinear oscillator's time domain approach. The method works on the principle of synchronisation of coupled oscillators with the general approach of VOC derived from a mutual coupling between the inverter and the control oscillator, leading to a convergence in dynamics to a common trajectory. This approach inherently allows the dynamics of the oscillator and inverter to influence each other. This will affect the common dynamics in the event of transient scenarios. Here we propose an improved mode of VOC, with an independent DC drive for the control oscillator, which provides a master-slave relation between the oscillator and inverter, thus enhancing the efficiency of VOC in the mitigation of transients under switching of different combinations of reactive loads. Further, a feedback strategy is proposed, wherein small perturbations in terms of the difference between the desired output and the real output of the inverter are introduced into the dynamics of the oscillator. This method is found to be effective in suppressing the disturbances induced during the switching of specific combinations of reactive loads. The results indicate that the proposed mode of VOC, with independent DC drive and delayed feedback, can provide considerable improvement in the performance of conventional VOC for inverter-based microgrids.

Keywords Virtual oscillator control(VOC), Van der pol(VdP) oscillator, coupling, delayed feedback, transients.

1. Introduction

The present-day emphasis on pollution-free generation and the need to preserve fossil fuels have accelerated research interest in renewable energy-based heterogeneous microgrids [1-4]. This has led to a tremendous shift in power generation modality from conventional large-scale power plants to localized distributed generation units. The main advantage of such units is their simplified mode of supply-demand fulfilment which has rendered it the capability of being an extremely reliable decentralized mode of power generation, which demands an autonomous nature under the islanded mode of such systems [5]. Despite the advantages of the microgrid in power system operation, ensuring a stable operation of the same under grid-connected as well as islanded modes has become a crucial prerequisite [6]. The varied nature of different sources connected to microgrids necessitates power electronic interfaces for their interconnection with the electrical grid [7]. This calls for the need to equip these interfaces with suitable control strategies to maintain stable operation in their grid-connected and islanded modes as well as during transitions between the two modes [8-10]. The need to accommodate the same controller for different modes of operation maintaining the voltage and frequency limits is challenging [11,12]. Renewable energy-based inverter-dominated microgrids are highly susceptible to variability in generation and are dominated by power electronic elements. This necessitates novel, robust as well as simple control schemes that can be realised on digital microcontrollers. In such cases, algorithmic simplicity becomes a crucial requirement considering the potential flexibility of microcontroller implementation.

Several control strategies have been extensively explored and proven effective for frequency control and load sharing between inverters. Droop-based control is one of the major control techniques for frequency and voltage regulation based on averaging voltage and current measurements and subsequent active and reactive power calculations [13,14]. Proportional Resonant (PR) controllers are the major modalities in droop control for grid-connected inverters compared to conventional Proportional Integral (PI) controllers in terms of steady-state tracking error reduction and disturbance rejection [15-18]. Added features like harmonic compensation have been implemented with similar control loops to tackle non-linear load dynamics [19]. Virtual synchronous machine (VSM) wherein power electronic converters are equipped with response features of a synchronous machine, which inherently provide frequency support and load sharing, is another established control approach for the islanded mode of operation [20]. Improvisation of control strategies based on the VSM approach for providing ancillary services like harmonic mitigation and reactive power support has been extensively studied [21,22]. Both droop control and VSM-based approaches rely on phasor measurements of voltage and current as well as average active and reactive power measurements. Hence the corresponding control loops become complex and challenging in terms of response time.

Virtual oscillator control(VOC) is a novel methodology that has gained momentum in the past few years, as a grid-forming control approach [23,24]. The concept of VOC originates from the idea of synchronization of coupled oscillators which has extensive application potential in varied fields [25,26]. Coupled oscillators are capable of providing self-sustained limit cycle oscillations with minimal computational complexity and fast response time [27]. VOC is implemented in the form of a limit cycle oscillator coupled to the inverter, thereby driving its state space trajectory to synchronise with the oscillator limit cycle having a specific frequency. VOC is a time domain approach which relies on instantaneous measurements of voltage and current of inverter and oscillator. Owing to these inherent features, VOC proves to be a promising approach capable of meeting the stringent voltage and frequency specifications in microgrids with the additional capability of fast synchronization of multiple inverters [28-32]. VOC-based inverters have been proven to withstand transient disturbance scenarios better than droop control [33, 34].

Oscillators are electronic circuits which are capable of producing sinusoidal output from an excitation which can generally be a DC source. A linear system is capable of generating oscillations only with an external time-dependent input whereas nonlinear systems are capable of generating self-sustained oscillations due to the inherent nonlinearity capable of maintaining the internal frequency [35-37]. Non-linear oscillators are characterized by limit cycles of constant amplitude and frequency and any initiated trajectory on this closed curve will stay on it unless disturbed externally [38]. Another distinguishing feature of a non-linear oscillator is its capability to synchronize with an external input signal, thus changing its natural oscillation frequency [39]. Van der Pol (VdP) oscillator has been the most widely implemented oscillator form in VOC applications though a large variety of other oscillators have been proposed in recent years [40]. Superior dynamic performance in terms of better response and overshoot has been exhibited with a different class of oscillators as shown in [41]. The design of VdP for islanded microgrids has been explicitly described in [42] regarding the terminal voltage of the inverter meeting the system specifications.

Synchronization and power sharing between parallel connected inverters are the most investigated topics under VOC applications. Conventional VOC models which are designed to utilize inverter output current are based on the implementation of coupled oscillator dynamics aimed at achieving fast synchronization and efficient power sharing. A vast majority of VOC-based proposals are mainly explored in the presence of resistive or inductive loads [43]. All these proposals deal with synchronization and power-sharing under changes in load which are either resistive or capacitive separately [43,44]. However, the effect of switching combinations of reactive elements, on the dynamics of power system controlled with VOC is rarely reported in literature. This points towards the necessity of investigating the performance of conventional VOC technique during such less explored load-switching scenarios.

In general, all VOC-based proposals follow the concept of mutual coupling between the inverter and controlling oscillators for achieving synchronization between them as well as between multiple inverters. In such a scheme, coupling from the inverter to the VdP provides a channel for the inverter to influence the dynamics of the VdP oscillator. Under such circumstances, transient events like load change which disturbs the dynamics of inverter voltage can disturb the VdP dynamics through the coupling signal of inverter voltage. Such conditions can lead to deviations in the frequency of the VdP limit cycle, thereby allowing a strong influence on total system dynamics.

Here in the proposed approach, the oscillator is provided with its drive and the coupling from the inverter to the oscillator is removed. This changes the scenario to a master-slave condition, wherein the VdP oscillator acts as the master thereby driving the trajectory of the inverter system towards its own [45]. Oscillator systems which require only an input source to produce sinusoidal oscillations can certainly prove to be useful as a unidirectional drive for controlling the inverter frequency to its stable limit cycle. In the proposed DC-driven scheme, the inverter trajectory is strongly pulled to the desired VdP oscillator trajectory and hence it is hypothesized that this form of coupling can provide robustness to the frequency of the VdP limit cycle, under transient event scenarios. Moreover, it is well established in dynamical systems theory that time-delayed feedback is effective in stabilizing state space trajectories [46,47]. Delayed feedback schemes are generally devised in the form of small perturbations which are proportional to the difference between the current state of the system from its previous state [48]. Once the two states converge on each other, the control signal vanishes. Feedback with a one-cycle delay has been a proven approach in stabilization and providing robustness to periodic trajectory [47-51]. In this work, a delayed feedback scheme is introduced along with an independent DC drive to the VdP oscillator to control the system dynamics under different types of load change scenarios. Performance of instantaneous as well as delayed feedback modes with different feedback forms namely fractional error, ERF and PI are analyzed comparatively in terms of power system parameters of voltage, current and frequency.

The organization of the manuscript is as follows: Section 2 gives the system description followed by Section 3 with results and discussion and Section 4 conclusion.

2. System Description

Figure 1 shows the representation of the proposed mode of VOC with an independent DC drive for VdP oscillator and unidirectional coupling from the VdP oscillator to the inverter. Here *R*, *L* and *C* represent the oscillator elements, and k_v and k_o represent the scaling factors.

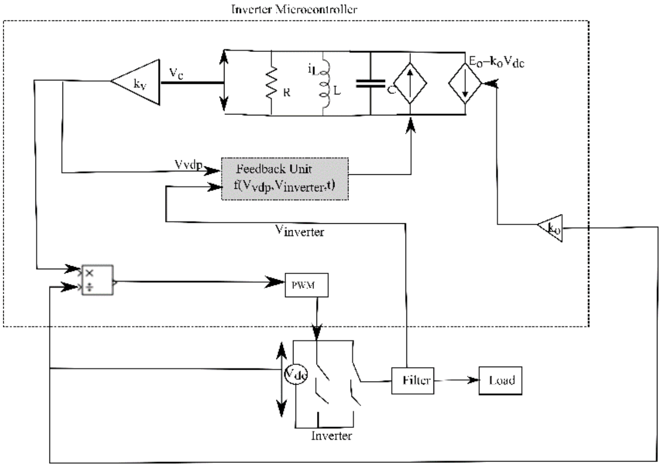

Fig. 1. Representation of DC-Driven Vdp with feedback forms for inverter control.

The dynamics of inverter-driven VdP in terms of oscillator elements *L* and *C*, conductance *σ*, coefficient of cubic current source *α*, voltage scaling factor k_v and input scaling factor k_i as in [40] are given by:

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

$$C\frac{dv_{vdp}}{dt} = -\frac{\alpha v_{vdp3}}{k_v^2} + \sigma v_{vdp} - k_v i_L - k_v k_i i \tag{2}$$

where *i* is the inverter current which is driving the VdP.

The proposed VdP with DC drive replaces the fraction of inverter current drive $k_i i$, with a DC source which in this case is taken from the inverter input similar to the input of a conventional oscillator. Hence equation (2) becomes:

$$C\frac{dv_{vdp}}{dt} = -\alpha v_{vdp}{}^3 + \sigma v_{vdp} - k_v i_L - k_v k_o V_{dc} \tag{3}$$

where V_{dc} is the input voltage to the oscillator and $k_{o=1/r}$, *r* being the resistance that provides the required current to drive the VdP.

To add delayed feedback along with this drive, a feedback current is fed in the form of a function dependent on instantaneous error voltage between the VdP oscillator output voltage scaled to the inverter voltage range and inverter terminal voltage. The feedback forms examined in the work are as follows:

$$\text{i) Error } \varepsilon = K_e(V_{vdp}(t) - V_{inverter}(t)) \tag{4}$$

$$\text{ii) ERF function } \operatorname{erf}(\varepsilon) = \frac{2}{\sqrt{\Pi}}\int_0^{\varepsilon} e^{-t^2}dt \tag{5}$$

$$\text{iii) PI function } H(\varepsilon) = K_p\varepsilon + K_i\int \varepsilon dt \tag{6}$$

where K_e is the fraction of the error

K_p and K_i denote PI coefficients.

The parameters of VOC and the system used in the investigation are tabulated in Table 1.

Table 1 Specifications of VOC and system

Description	Value
Voltage Scaling Factor (K_v)	178 V/V
Input Scaling Factor (K_o)	0.15A/A
Conductance(σ)	6.09 Ω^{-1}
Harmonic oscillator capacitance (C)	0.18 F
Harmonic oscillator inductance (L)	3.94 x 10^{-5} H
Inverter DC link Voltage	180 V
Nominal system frequency	2π*60 rad/sec
Base load	R=20Ω, L= 0.1 H
Step-up load	R=100Ω, L= 0.5 H
RLC load	R= 40 Ω, 0.2 H, 1 μF

3. Results and Discussion

The performance evaluation of two forms of VOC using 1) VdP with a DC drive and 2) VdP with a DC drive along with feedback is conducted in terms of the evolution of power system parameters and is compared with that of conventional VOC with an inverter current drive. By adopting an independent DC drive, the coupling from the inverter side is effectively eliminated and the system becomes equivalent to one with unidirectional coupling between VdP and inverter. Introducing feedback as a function of the error between the scaled output of VdP and the inverter output will provide stronger control of the inverter output towards the desired VDP limit cycle trajectory. The behaviour of the inverter system with these two control approaches under dynamic scenarios is compared in terms of initial settling time and overshoots in power system parameters of Point of Common Coupling (PCC) voltage, output current and frequency. The behaviour of the system is investigated for a steady state load condition of (a) base RL load, as well as dynamic switching scenarios wherein two forms of additional loads are switched at 3 s (b) 5 times the base load and (c) an RLC load. The performance of DC-driven VdP is compared with the conventional VOC with inverter current as drive, and the results of the investigation are tabulated in Table 2. The overshoots have been compared with standards in [52].

Table 1. Comparison of different modes of DC-driven VdP feedback forms

DC-driven VdP Vs Conventional VOC									
No feedback									
	Base Load	5 times load switched at 3 s				RLC load switched at 3 s			
VdP Type	*THD in %*	*% change in voltage*	*% change in current*	*% change in frequency*	*THD in %*	*% change in voltage*	*% change in current*	*% change in frequency*	*THD in %*
Conventional	2.44	5.67	13.2	0.52	2.76	56.62	155.62*	12.54*	3.14
DC-driven	3.29	3.87	8.4	0.32	3.6	38.07	140.31*	8.25*	3.94
Error feedback									
	Base Load	5 times load switched at 3 s				RLC load switched at 3 s			
Feedback Mode	*THD in %*	*% change in voltage*	*% change in current*	*% change in frequency*	*THD in %*	*% change in voltage*	*% change in current*	*% change in frequency*	*THD in %*
Instantaneous	3.34	6.36	18.09	0.57	3.5	67.4*	219.2	21.9*	3.62
Delayed	2.19	3.25	7.7	0.43	2.25	29.1*	90.06	3.3*	2.31
ERF feedback									
	Base Load	5 times load switched at 3 s				RLC load switched at 3 s			
Feedback Mode	*THD in %*	*% change in voltage*	*% change in current*	*% change in frequency*	*THD in %*	*% change in voltage*	*% change in current*	*% change in frequency*	*THD in %*
Instantaneous	3.29	4.5	5.03	0.32	3.46	46.71*	155.14	10.9*	3.6
Delayed	3.45	0.67	0.8	0.34	3.33	1.06	0.35	0.7	3.44
PI feedback									
	Base Load	5 times load switched at 3 s				RLC load switched at 3 s			
Feedback Mode	*THD in %*	*% change in voltage*	*% change in current*	*% change in frequency*	*THD in %*	*% change in voltage*	*% change in current*	*% change in frequency*	*THD in %*
Instantaneous	3.35	6.36	14.8	0.5	3.5	67.14*	165	21.7*	3.62
Delayed	3.23	1.08	4.9	0.37	3.38	15.34*	18.9	0.57	3.49

*-overshoot values as compared to standards in [52]

3.1. Steady State Evolution

Here we investigate the performance of the conventional form of VOC with drive current acquired from the inverter and DC-driven VdP for a base load of 20 Ω, 0.1 H as well as dynamical scenarios of different types of load switching.

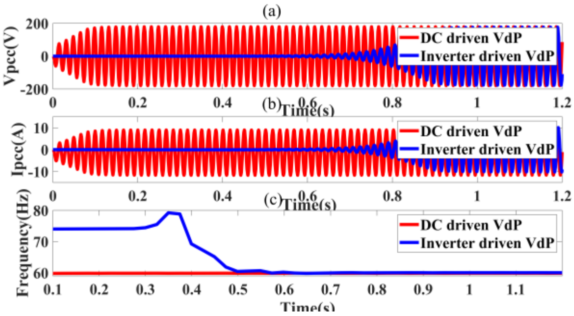

Fig.2. Steady-state evolution of a) PCC voltage b) PCC current and c) frequency for DC-driven and inverter-current-driven VdP.

Figures 2(a-c) show the evolution of PCC voltage, output current and frequency for DC-driven and inverter current-driven VdPs feeding the base load specified in Table 1. From Figure 2(a), it can be seen that for inverter-driven VdP, the PCC voltage takes about 1.02 s to overcome the initial transient state and settle down to a stable limit cycle whereas, for DC-driven VdP, the settling time is 0.165 s which is considerably shorter. The same pattern can be observed in Figure 2(b) representing the evolution of output current wherein the settling time is 0.16 s compared to the settling time of 1.02 s for the conventional VdP with inverter drive. This effect of a shorter transient state is evident in the dynamics of frequency also which can be observed in Figure 2(c). Herein, compared to the 0.5 s settling time in inverter current-driven VdP, DC-driven VdP does not have any significant length of settling time and the system attains a stable output frequency from the beginning. These results evidence the advantage of controlling the inverter using a VdP with an independent DC drive source in contrast to the performance of conventional VOC where its settling time considerably affects the settling of inverter output. The corresponding value of THD for the DC-driven VdP is about 3.29% which is slightly higher than the THD obtained with conventional VOC with a value of 2.44 %. However, these values are well within the upper limit of THD < 8% of IEEE-519 standards.

Further, the effect of the DC drive scheme for VdP in controlling inverter dynamics under two types of dynamic conditions of load switching is investigated.

3.2. Dynamic Evolution

Here we consider the effect of switching a step-up load of 5 times the base load and an RLC load at 3s on an inverter controlled with DC-driven VdP and compare it with that of conventional VOC.

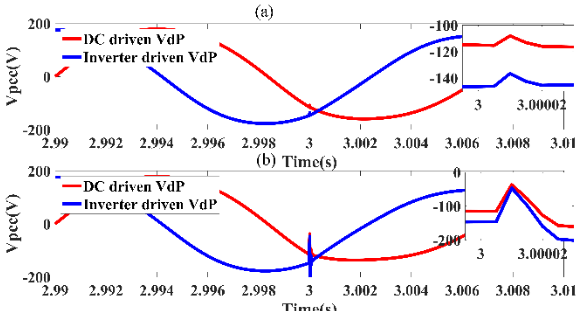

Fig. 3. Dynamic evolution of PCC voltage for DC-driven VdP in case of (a) 5RL switching and (b)RLC switching.

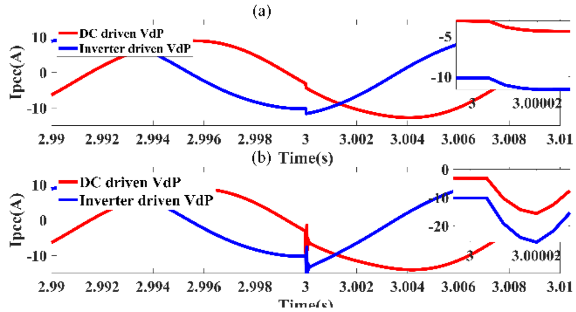

Fig.4. Dynamic evolution of PCC current for DC-driven VdP in case of (a) 5RL switching and (b)RLC switching.

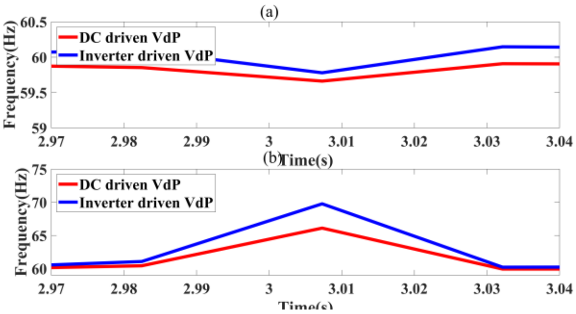

Fig. 5. Dynamic evolution of frequency for DC-driven VdP in case of (a) 5RL switching and (b)RLC switching.

Figures 3(a) and (b) show the evolution of PCC voltage, 4 (a) and (b) show PCC current and 5 (a) and (b) show the frequency for inverter controlled using DC-driven VdP for switching of 5 times base load and an RLC load at 3s. The same condition is implemented for inverter controlled with conventional VOC and the corresponding results are given in the same figure. It is observed that in the case of switching of 5 times load, there is a reduction in the change incurred in the voltage at PCC for the DC-driven VdP, which is just 3.87% whereas it is about 5.67 % in the case of conventional VOC. Similarly, the fluctuation in current can be found to reduce to 8.4 % for DC-driven VdP from a high value of 13.2% for conventional VOC. The evolution of frequency also evidences the efficiency of controlling the inverter using DC-driven VdP for which the frequency shift at the switching instant is 0.32%. This is lower than the case of conventional VOC where the frequency change is about 0.52 %. These advantages obtained during load switching are in addition to the advantage of negligible settling time and thereby delay in outputs which are generally observed for conventional VOC. In the case of DC-driven VdP, THD obtained for this case of load switching is in the range of 3.6 % for VdP with DC drive whereas in conventional VOC using VdP with inverter drive it is about 2.76 %. However, both these ranges differ only by a small margin of 0.84 % and are within the IEEE 519 limits for THD of less than 8 %.

In the case of switching an RLC load, it is found that the surge in voltage during load switching is about 56.62% in the case of the inverter controlled with conventional VOC whereas the voltage increase is reduced to 38.07 % in the case of VOC with DC-driven VdP. Similarly, the change in current for inverter controlled with DC-driven VdP is reduced to 140.31% from 155.62 % for conventional VOC controlled inverter. Figure 5 (c) also evidences a similar advantage with the frequency shift reduced to 8.25 % with DC-driven VdP from 12.54 % of conventional VOC.

Though the shifts obtained with DC-driven VdP are lower than conventional VOC for RLC load switching, these values are not within the IEEE 1547 standards stipulated limits of +10% and -12% for voltage and +2% and -2.5 % for frequency [52]. It is hypothesized that maintaining the VdP oscillator limit cycle more robustly with a better mode of operation can effectively restrain the deviations in power system parameters under switching conditions. For this purpose, we propose a method of providing a feedback signal proportional to the difference between the inverter output and the scaled output of the VdP oscillator. Two forms of feedback, instantaneous and delayed, are provided for better performance under switching effects.

3.3 DC-Driven VdP with Feedback

To overcome the limitation of VOC with a DC drive in terms of the overshoot of power system parameters during RLC switching, a feedback mode is proposed and its performance is evaluated in terms of voltage, frequency and current. Three different feedback forms namely error, ERF and PI are tested in terms of these power system parameters.

3.3.1 Error feedback

In this section, the results of the performance comparison between instantaneous and delayed modes of error feedback under load change conditions are presented.

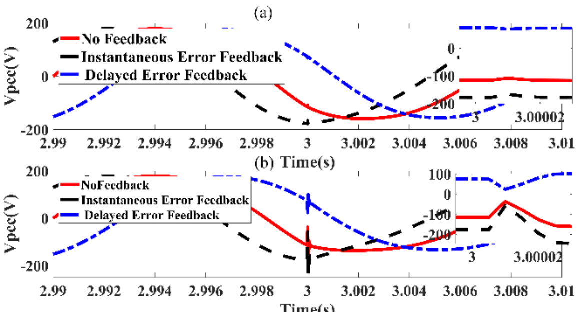

Fig. 6. Dynamic evolution of PCC voltage for DC-driven VdP with error feedback for (a) 5RL switching and (b) RLC switching.

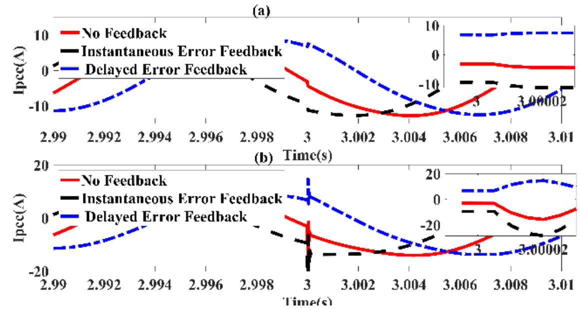

Fig. 7. Dynamic evolution of PCC current for DC-driven VdP with error feedback for (a) 5RL switching and (b) RLC switching.

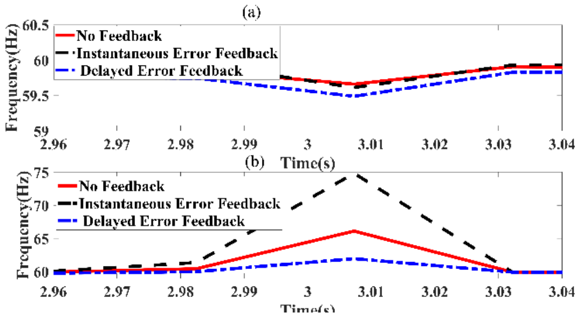

Fig. 8. Dynamic evolution of frequency for DC-driven VdP with error feedback for (a) 5RL switching and (b) RLC switching.

Figure 6 shows the evolution of PCC voltage for DC-driven VdP with error feedback under dynamic conditions of (a) 5RL load switching and (b) RLC load switching for three cases 1) DC-driven VdP without feedback 2) DC-driven VdP with instantaneous feedback and 3) DC-driven VdP with delayed feedback, and figure 7 shows the corresponding evolution of output current. From Figure 6, it can be inferred that there is no significant disturbance in PCC voltage under 5RL switching, and hence not much advantage can be observed with any feedback modes. In the case of RLC switching wherein the system is adversely affected by its switching, the delayed feedback displays the most ideal performance. The percentage change in voltage is 3.25% for the delayed error feedback. From Table 2, it can also be observed that this form of feedback provides the lowest value of THD, though THD for all forms are well within IEEE 519 standard limits of less than 8%. Similar performance is observed in Figure 7(a) and (b) showing the evolution of the output current about the different modes of feedback. The percentage deviation in delayed error feedback is considerably low with a value of 3.2% which is much lower compared to that of 8.4% and 13.2% for the DC-driven and conventional VdP.

Figure 8 shows the evolution of frequency for DC-driven VdP with error feedback under dynamic conditions of (a) 5RL load switching and (b) RLC load switching for the three cases of DC-driven VdP. From Figure 8 (a) it can be observed in the case of 5RL switching, there is no drastic deviation in frequency in any of the feedback forms. However, for RLC switching delayed feedback is found to be the best-performing mode. Here the percentage change in frequency is 3.3% for delayed feedback which is much less than conventional VOC as well as DC-driven VdP, but slightly higher than the stipulated value of 2% as seen in Table 2. THD for all forms of feedback is within the allowed limits wherein the lowest value is obtained with a delayed feedback form of 2.19%.

3.3.2 ERF feedback

Here the results of the performance comparison between instantaneous and delayed forms of ERF feedback under load change conditions are discussed.

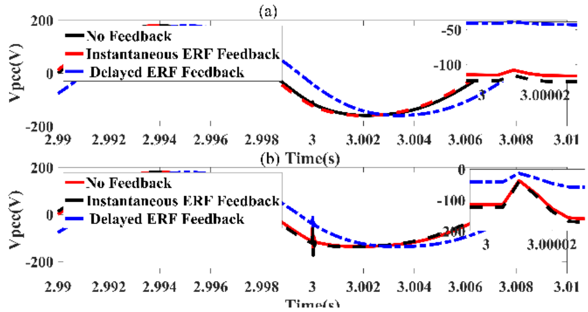

Fig. 9. Dynamic evolution of PCC voltage for DC-driven VdP with ERF feedback for (a) 5RL switching and (b) RLC switching.

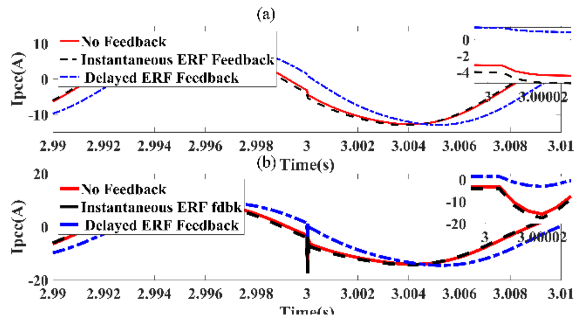

Fig. 10. Dynamic evolution of PCC current for DC-driven VdP with ERF feedback for (a) 5RL switching and (b) RLC switching.

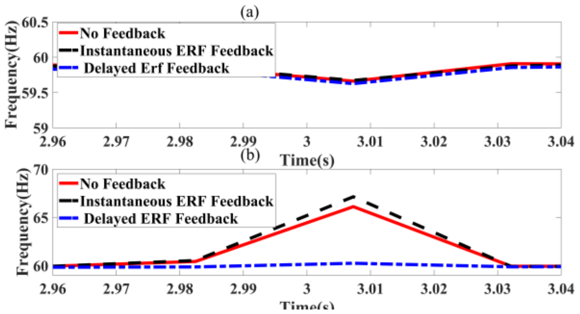

Fig. 11. Dynamic evolution of frequency for DC-driven VdP with ERF feedback for (a) 5RL switching and (b) RLC switching.

Figure 9 shows the evolution of PCC voltage for DC-driven VdP with ERF feedback under dynamic conditions of (a) 5RL load switching and (b) RLC load switching for three cases 1) DC-driven VdP without feedback 2) DC-driven VdP with instantaneous feedback and 3) DC-driven VdP with delayed feedback, and figure 10 shows the corresponding evolution of output current. From Figure 9(a) it can be observed that in the case of 5 RL switching, the percentage change in PCC voltage shown by ERF feedback is within the allowed limits for both modes of feedback. Figure 9(b) which shows the dynamics of PCC voltage for RLC load switching, indicates that the transient overshoot in this case is considerably higher compared to the case of 5RL switching. Herein the effect of delayed feedback is evident wherein the overshoot in PCC voltage for delayed feedback is 1.06% which is comparatively very much lower than the value of 46.71% obtained with instantaneous ERF feedback as well as 56.62% conventional VOC and 38.07 % of VOC with DC-driven VdP as seen from table 2. Figure 10 indicates that the transient dynamics is significant only in the case of RLC switching whereas in the case of 5RL switching it is very negligible as observed in the figure. The delayed feedback form is the most efficient mode for control of transient dynamics wherein the overshoot is only 0.35 %.

Figure 11 shows the evolution of frequency for DC-driven VdP with ERF feedback under dynamic conditions of (a) 5RL load switching and (b) RLC load switching for three cases 1) DC-driven VdP without feedback 2) DC-driven VdP with instantaneous feedback and 3) DC-driven VdP with delayed feedback. From the figure, it can be observed that in the case of 5RL switching, the deviation in frequency is only marginal whereas in the case of RLC switching, there is considerable deviation in frequency. In this case of RLC switching, delayed feedback performs the best providing a frequency deviation of 0.7 %, which is far less than that of conventional VOC as well as DC-driven VdP as seen in Table 2. The performance of instantaneous feedback lies below conventional VOC but is higher than DC-driven VdP and herein only delayed form provides frequency control within the allowed limits. In the case of 5RL and RLC switching, the value of THD in both modes is lower compared to DC-driven VdP but higher than conventional VOC. However, all these values lie well within the THD stipulated limits.

3.3.3 PI feedback

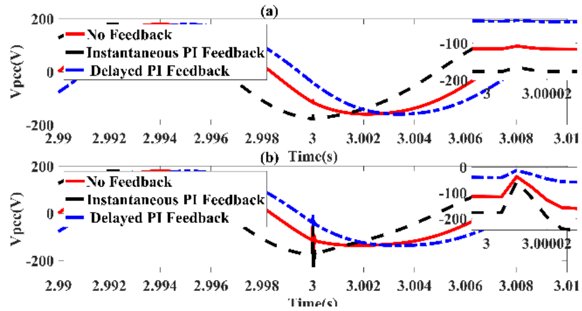

Fig. 12. Dynamic evolution of PCC voltage for DC-driven VdP with PI feedback for (a) 5RL switching and (b) RLC switching.

Figure 12 shows the evolution of PCC voltage for DC-driven VdP with PI feedback under dynamic conditions of (a) 5RL load switching and (b) RLC load switching for three cases 1) DC-driven VdP without feedback 2) DC-driven VdP with instantaneous feedback and 3) DC-driven VdP with delayed feedback, and figure 13 shows the corresponding evolution of output current. From Figure 12(a) it can be observed that in the case of 5 RL switching, no significant change is observed in PCC voltage and the values are all well within the allowed limits for both modes of feedback. The percentage change in voltage is within the limits for 5RL switching in all feedback modes.

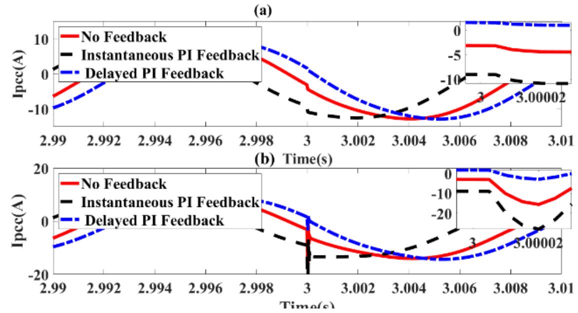

Fig. 13. Dynamic evolution of PCC current for DC-driven VdP with PI feedback for (a) 5RL switching and (b) RLC switching.

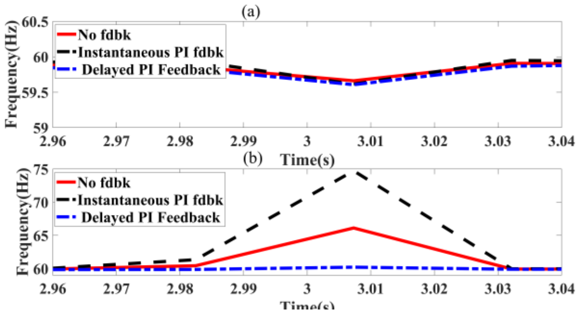

Fig. 14. Dynamic evolution of frequency for DC-driven VdP with PI feedback for (a) 5RL switching and (b) RLC switching.

Similar to the evolution of PCC voltage, no significant perturbations are observed in the evolution of output current as seen in Figure 13 (a) and the evolution patterns are similar to each other for all modes of feedback. From Figure 12(b) the effect of delayed feedback is evident wherein the overshoot in PCC voltage for delayed feedback is 15.34% which is below the value of 67.14% obtained with instantaneous PI feedback as well as 56.62% of conventional VOC and 38.07 % of VOC with DC-driven VdP as seen from table 2. Similar performance is observed in Figure 13(a) and (b) showing the evolution of the output current for the different modes of feedback. In the case of THD, the performance of DC-driven VdP is marginally lower compared to conventional VOC. However, all the values are well within the IEEE-defined THD limits of less than 8% for all forms of feedback.

Figures 14(a) and (b) show the evolution of frequency for DC-driven VdP with PI feedback under the above-discussed load-switching conditions for the different modes of feedback. From these figures, it can be observed that in the case of 5RL switching in Figure 14(a), the deviation in frequency is minimal whereas a considerable amount of deviation is present in frequency evolution in the case of RLC switching shown in Figure 14(b). Delayed feedback can be observed to provide efficient control compared to all other types in the case of RLC switching. The percentage change in frequency is as low as 0.57 % as observed from Table 2 which is considerably lower than the instantaneous feedback as well as conventional VOC and DC-driven VdP.

Employing the proposed unidirectional drive from VdP to the inverter is found to be advantageous in terms of reduction in settling time as well as control of overshoots in voltage and current and frequency deviations during switching of 5 times the base RL load. In the case of RLC load switching, the percentage overshoot in PCC voltage and frequency are considerably higher than the IEEE stipulated limits. The introduction of delayed feedback equips the system with efficient transient mitigation capability. ERF and PI forms of feedback perform better than simple error feedback forms, among which the ERF form exhibits remarkable performance in controlling the disturbance amplitude and frequency shift during load change.

4. Conclusion

In the conventional VOC, the disturbances generated at the inverter side influence the dynamics of the control oscillator through the mutual coupling provided between them which acts as a convenient pathway for the same which leads to inherent deterioration of the robustness of the oscillator limit cycle, under vigorous load-switching scenarios. To address this issue and enhance control performance, a new approach of unidirectional coupling from the control oscillator to the inverter is proposed. For this purpose, the traditional form of VdP is employed, wherein a DC source drives the oscillator which further drives the inverter through a uni-directional coupling signal. Though the proposed DC-driven VdP control technique is effective in lowering this transient overshoot, it is not efficient enough to bring these parameters within the IEEE limits. Hence, a feedback strategy which can stabilize the limit cycle trajectory of the control oscillator is further presented. Investigations on the various forms of feedback suggest that a delayed feedback mode can perform better than instantaneous feedback as well as a pure DC drive mode in controlling the transient dynamics. Among the various forms of the proposed methodology, delayed ERF feedback proves to be highly efficient in improving the performance of VOC in controlling the disturbances in power system parameters during transient changes with negligible impact on THD. This provides a simple and robust control scheme for inverter-dominated renewable energy-based microgrids.

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