

An Adaptive Controller for D-STATCOM under Parametric Uncertainties in Output Filter and Load Variations

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Abstract:

D-STATCOM is an important component to compensate for the required reactive power in the distribution lines. Generally, a cascaded PI control structure is used to control a D-STATCOM. However, the performance of this conventional PI-based loop control deteriorates under the output filter and severe load variations. To mitigate the negative effects of such variations on the D-STATCOM performance, this paper proposes a novel approach not need the accurate model of the system. This new method exploits an adaptive controller in the current loop and a conventional PI controller in the voltage loop. The simulation and hardware experimental results indicate this new controller provides low total harmonic distortion (THD), robustness against parameter and load variations, and fast transient response.

Keywords: D-STATCOM, Cascade Loop Control, Adaptive Lyapunov-based Control, Parameter Variations, Load Variations.

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Nomenclature

Symbol	Description
V	Bus Voltage (line-to-line)
E	Terminal Voltage (line-to-line)
X	Reactance of Output Filter
P	Active Power
Q	Reactive power
L	Inductance of Output Filter and transformer
R	Resistance of Output Filter and transformer
C	Capacitance of DC-link
R_p	Resistance of DC-link (loss model)
i_{dc}	Current of DC-link
V_{dc}	Voltage of DC-link
V_d	d -component of Bus Voltage in d - q frame
V_q	q -component of Bus Voltage in d - q frame
E_d	d -component of Terminal Voltage
E_q	q -component of Terminal Voltage
i_d	d -component of AC Current
i_q	q -component of AC Current
ω	Angular Frequency

1. Introduction

The advancements in the power electronics switch pave the way toward the introduction of the flexible AC transmission system (FACTS) equipment in the power system. These devices increase the speed and reliability of the system [1]. Distribution Static Compensator (D-STATCOM) is a FACTS equipment constructed based on voltage source converter (VSC), and it is a shunt reactive power compensator in the distribution power lines. Recently, the use of the D-STATCOM in the distribution lines has been taking a great deal of attention due to its ability to enhance the stability of the power plant and reduction of total harmonic distortions (THD) at PCC [1].

To implement a D-STATCOM in real-world applications, researchers have suggested various control approaches to address the control issues and the practical limitations in which they have involved. To deal with these problems and control the dynamic behavior of D-STATCOM, a cascaded loop control structure of the Proportional-integral (PI) controllers in the dq -frame was proposed [2]. In this structure, the PI controller in the outer loop guarantees the tracking of the DC link voltage, and the inner loop controllers ensure the fast reactive power compensation through controlling the current components in the dq -frame.

Using different types of PI controllers in the cascaded loop structure [3–9], results showed that the proper tuning of the controller parameters would lead to the desired performances in the D-STATCOM. The tuning of the PI-based controllers is highly dependent on the system characteristics—the filter parameters, DC-link capacitance, and the operating conditions. Indeed,

variations in the filter parameters or large disturbances like sudden load variations could cause performance degradation. Additionally, the output filters could prompt oscillatory and unstable dynamic behavior [7]. Passive damping [8] and active damping [9] have extensively used to fix the filter resonances. However, passive approaches cause a decline in the overall efficiency since the power losses provoked by additional resistive elements, and the active damping approaches are highly dependable to the sensitivity of the filter variations. In an attempt to achieve plausible performance in the presence of filter uncertainties and the load variations, researchers have been proposing the linear-quadratic regular (LQR) based controllers [3,10–13]. These approaches have used to convert the tuning PI to gain a problem in solving an optimal equation in the state space representation. In such methods, the tuning of the optimal coefficients requires the expertise of the designer, and uncertainty in filter parameters has not been addressed.

Fuzzy-based PI controllers were proposed in [11–14] to address the gain design problem. Such methods highly rely on the designer's initial choices and impose a heavy computational load on the controller design procedure. To cope with the initial condition problem, a new population-based optimization algorithm was proposed in [15]. However, this method has excessive computational load; thus, it would have difficulties to implement in real-world applications. In the cascade structure, the inner control loop of the electronic equipment such as D-STATCOM, voltage source inverters (VSI), grid forming inverter (GFI), etc. have the same configuration. Regarding this, in these devices, to deal with the variations in filter parameters, other control techniques such as predictive control [16] and neural-network-based control [17] have been presented.

Recently, a sliding mode controller (SMC) has been devised to address the aforementioned problems and reduce the THD in the presence of the parameter uncertainties and the external disturbances to control a GFI [18]. The main drawback of this SMC controller is the large controller gains leading to the high amplitude fluctuations in the system's variables because of the bang-bang characteristic of the sliding surface. Such oscillations could the control boundary region touch the protection limits in large sudden external disturbances. In this paper, an adaptive Lyapunov based control is devised and applied in the inner-loop, and a conventional PI controller is used in the outer loop.

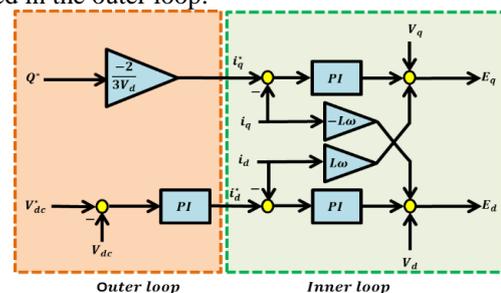


Fig. 1. Conventional configuration of cascaded loop control

The proposed configuration would give the advantages of constant switching frequency, low THD, robustness and fast transient response of the system in the presence of variations in filter parameters and large external disturbance such as severe load variations.

The rest of this paper is structured as follows. Section 2 reviews the D-STATCOM's structure, the system equations, conventional PI-based cascaded-loop control strategy. At the end of this Section, the influence of variation in filter parameters is shown on the system's dynamics. Section 3 proposes an adaptive Lyapunov based controller in the inner loop to address the issues in Section 2. Section 4 gives simulation evaluation, and Section 5 presents the hardware and experimental validation of the proposed approach. Finally, the paper concludes in Section 6.

2. Model of D-STATCOM

D-STATCOM is a VSC based shunt reactive compensator that connects parallel with the distribution power lines. The structure of a D-STATCOM is shown in Fig. 2. The connection between the VSC and the system is linked through the AC output filter and the coupling transformer. Based on the power convention, the exchanged active and reactive powers by the D-STATCOM from the supply are expressed in (1) and (2) as [1]

$$P = \frac{EV}{X} \sin \delta \quad (1)$$

$$Q = \frac{V}{X} (E \cos \delta - V) \quad (2)$$

where δ is the phase angle between the output of the VSC and AC grid voltages.

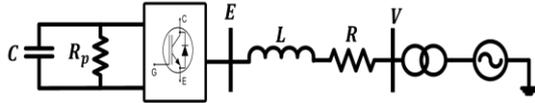


Fig. 2. D-STATCOM configuration

Considering (1) and (2), E plays a major role in D-STATCOM compensation mode and the rate of compensation. In capacitive mode, when D-STATCOM injects reactive power to the grid, E must be greater than grid voltage, and E should be lower than grid voltage in the inductive mode. With this mind, E is the manipulator signal that regulates the reactive power. As shown in Fig. 2, the state space equations of the AC part of a D-STATCOM in the dq-frame is stated as [1]

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega \\ \omega & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L} \begin{bmatrix} E_d - V_d \\ E_q - V_q \end{bmatrix} \quad (3)$$

The derivative equation that indicates the behavior of the DC link of the D-STATCOM in the state space is described as

$$\frac{dV_{dc}}{dt} = \frac{-1}{C} i_{dc} - \frac{V_{dc}}{R_p C} \quad (4)$$

Regarding the power balance equation between AC and DC terminals of the VSC, one achieves the equation (5) that shows the relation between the variables of the system.

$$V_{dc} i_{dc} = \frac{-3}{2} (E_d i_d + E_q i_q) \quad (5)$$

Thus, considering (4) and (5), the dynamic relation between DC voltage link and the state variables of the AC-side is derived as follows:

$$\frac{dV_{dc}}{dt} = \frac{3}{2CV_{dc}} (E_d i_d + E_q i_q) - \frac{V_{dc}}{R_p C} \quad (6)$$

Indicated in Fig. 1, the outer loop generates the reference signals for the inner loop. To this purpose, a PI controller is used in the DC voltage regulation loop to generate current references in the dq-frame directly is extracted from the required reactive power in the inner loop. By using PI controllers and system equations, the switching reference signals are generated and sent to the switches by the PWM module. In cascaded loops structure, a higher bandwidth controller in the inner-loop requires than the outer-loop controller for converters with a high switching frequency, and Low switching frequency conduce a narrow stable operation range [19]; thus, the PI controllers design need a trade-off between switching frequency and desired characteristics. In operational mode, the filter parameter values deviate from the nominal value [18]. To address the variations in RL filter parameters, it requires an accurate model of the AC-side of D-STATCOM. Hence the inductance and resistance of the AC-side filter are modeled as

$$L = L_0 + \Delta L$$

$$R = R_0 + \Delta R$$

where L_0 and R_0 are nominal values, and ΔL and ΔR show the parameter uncertainties in the filter. Hence, one can rewrite (3) as

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_0}{L_0} & \omega \\ -\omega & -\frac{R_0}{L_0} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_0} \begin{bmatrix} E_d - V_d \\ E_q - V_q \end{bmatrix} + \begin{bmatrix} \Delta_d \\ \Delta_q \end{bmatrix} \quad (7)$$

where Δ_d and Δ_q in (6) is expressed as

$$\Delta_d = \left(\frac{-R_0(L_0 + \Delta L - 1)}{L_0 + \Delta L} - \frac{\Delta R}{L_0 + \Delta L} \right) i_d - \frac{L_0 + \Delta L - 1}{L_0 + \Delta L} (E_d - V_d) \quad (8)$$

$$\Delta_q = \left(\frac{-R_0(L_0 + \Delta L - 1)}{L_0 + \Delta L} - \frac{\Delta R}{L_0 + \Delta L} \right) i_q - \frac{L_0 + \Delta L - 1}{L_0 + \Delta L} (E_q - V_q)$$

The accurate model a D-STATCOM is expressed by (3), (7) and (8). As shown in (8), the impact of the uncertainties in the filter parameters could be shown as the disturbance signal in the state equations. This signal is a function of the system variables, the nominal value of filter parameters, and unknown variables (the filter parametric variations). Thus, the conventional controllers like PI that control the system around its equilibrium point, so they are more vulnerable to fail when dealing with these disturbances. Based on the variability of such

conservative approach in control system design. Indeed, these methods analyze the system behavior in the worst case and try to design controllers to keep the system stable and meet tracking criteria in these conditions. Hence, the control system will have a conservative behavior even in normal cases that causes to degrade the system performance.

In addition, designing such passive controllers is highly dependent on the considered worst-case scenario, and if a phenomenon occurs in the system that a designer could not regard in the design process, the stability of the system could be endangered and the system fails. On the other hand, the proposed adaptive approach has this merit to adapt the control law based on the system's variations, and it shows a good performance under such scenarios. This could be seen clearly in sudden load changes.

4. Simulation Results

The proposed control algorithm was evaluated and compared with the conventional PI-based control strategy through simulation studies using MATLAB/SIMULINK/SimPowerSystem (SPS). A 5kVA D-STATCOM was considered, and the system data is shown in Table 1. The parameters of the cascaded-loop PI controllers were designed according to [1], [19].

Assume the maximum perturbation in the parameters of the filter is 30% around their nominal values. Then, for the proposed controller, w and K were set to 30 and 60, respectively. The case study involves three scenarios, scenario1, scenario 2, and scenario 3, corresponding to the parameter uncertainty of L and R at 0%, 30%, and -30%, respectively. For three scenarios, two different control methods are implemented distinctly to control the D-STATCOM. The two control strategies are 1) Adaptive Lyapunov based controller for the inner loop and PI for the outer loop (PIAL), and 2) PI-based control strategies for both inner and outer loops (PIPI).

Figure 4 compares the dynamic responses for reactive power compensation at the PCC using the two different control strategies when the demanding reactive power at the PCC has a variable profile like under scenario 1, scenario 2, and scenario 3, respectively. According to Fig. 4, the PIPI strategy shows the lowest response in presence of uncertainty under scenario 2 and under scenario 3, the PIPI strategy response to changes in load shows undamped fluctuations in compensated reactive power of the D-STATCOM in inductive mode.

As shown in Fig. 4, the proposed PIAL strategy shows the fastest response speed, lowest overshoot, and demonstrates better tracking performance and robustness against uncertainties than the PIPI. The performance of the proposed strategy against PIPI can also be seen in Fig. 5, which compares the DC-voltage tracking using the two different control strategies.

Figures 6-8 compare the compensated current and the voltage waveforms of the *phase a* at the PCC using PIAL and PIPI control strategies under scenario 1, scenario 2, and scenario 3, respectively. As shown in Figs. 6-8, the

PIAL strategy has a faster recovery speed and better output voltage and current quality against uncertainties.

Table 1. Three phase D-STATCOM system parameters

Symbol	Value	Description
S_n	5kVA	Rated Power
V	400V	line-to-line Voltage
f	50Hz	Fundamental Frequency
f_{sw}	10kHz	Switching Frequency
f_{sam}	20kHz	Sampling Frequency
V_{dc}	700V	DC-link Voltage
L	10mH	Inductance of Output Filter
R	0.4Ω	Resistance of Output Filter
C	220μF	Capacitance of DC-link

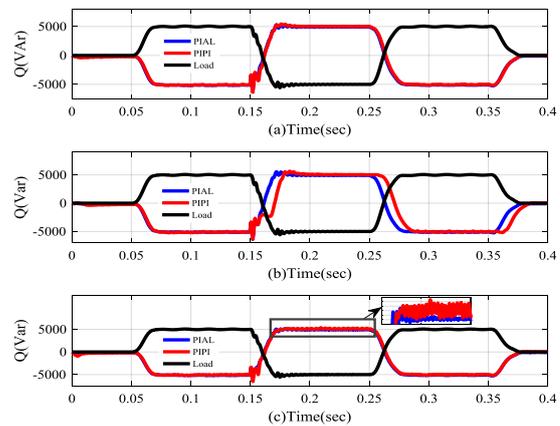


Fig. 4. Reactive power compensation of D-STATCOM under (a) Scenario 1; (b) Scenario 2; (c) Scenario 3

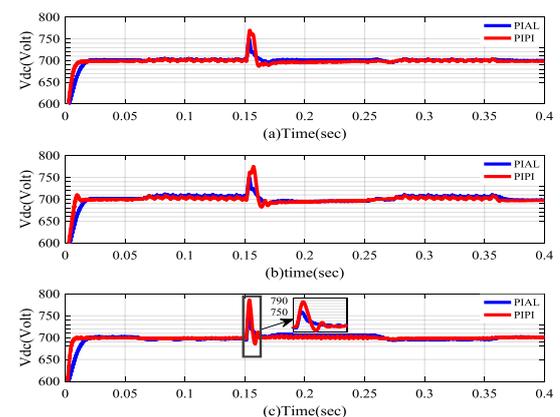


Fig. 5. DC-voltage waveform response under (a) Scenario 1; (b) Scenario 2; (c) Scenario 3

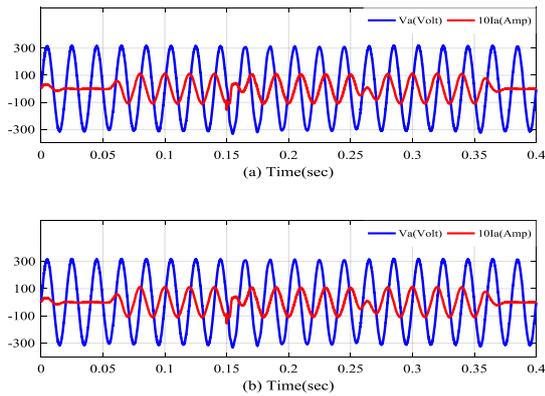


Fig. 6. Compensated current and the voltage waveforms of phase a under scenario 1 (a) PIAL; (b) PIPI

Tables 2 and 3 show the comparison of voltage and current THD at the PCC by using PIAL and PIPI control strategies under three scenarios for the four different stages of reactive compensation based on the load variations. As shown in Tables 2 and 3, the proposed control strategy has a lower voltage and current THD under all the load conditions against uncertainties in filter parameters. This demonstrates that the proposed control strategy has better robustness against the external disturbance and better power quality than the PI control strategy.

Table 2. The PCC voltage's THD

Controller	PIPI			PIAL		
	Time(s)	0.12	0.22	0.32	0.12	0.22
Scenario 1 (%)	1.23	0.49	1.32	1.29	0.50	1.47
Scenario 2 (%)	1.18	0.37	1.12	0.96	0.42	1.02
Scenario 3 (%)	2.17	6.61	2.12	2.11	0.52	1.91

Table 3. The Compensated current's THD

Controller	PIPI			PIAL		
	Time(s)	0.12	0.22	0.32	0.12	0.22
Scenario 1 (%)	3.82	1.61	3.81	2.45	1.69	2.69
Scenario 2 (%)	5.17	1.36	5.24	3.60	1.38	3.63
Scenario 3 (%)	2.76	7.62	2.57	2.17	2.80	2.62

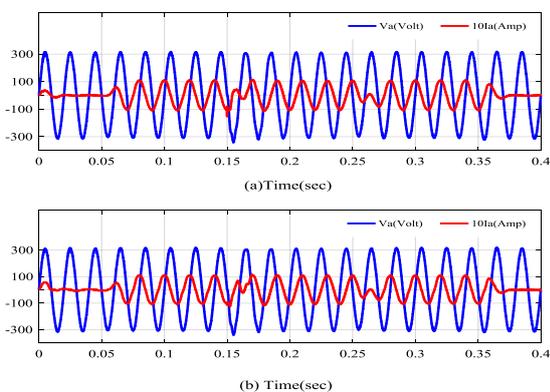


Fig. 7. Compensated current and the voltage waveforms of the phase a under scenario 2 (a) PIAL; (b) PIPI

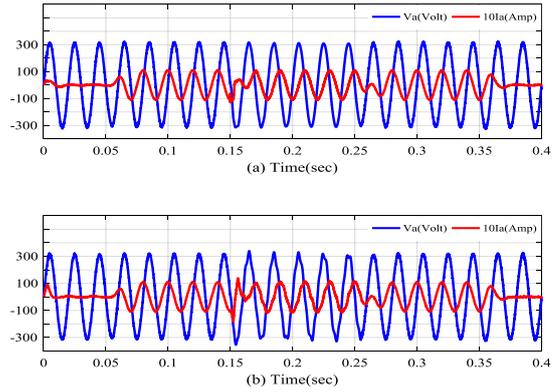


Fig. 8. Compensated current and the voltage waveforms of phase a under scenario 3 (a) PIAL; (b) PIPI

5. Experimental Results

To validate the proposed algorithm experimentally, a 5kVar three-phase two-level D-STATCOM was built. A prototype of the experimental setup is shown in Fig. 9, and its parameters for hardware experiments are given in Table 1. The control algorithm is implemented using a TMS320F28335 (150MHz) DSP chip. The controller parameters for both PIPI and the proposed approach, PIAL, are redesigned. Then the system was tested under the three scenarios mentioned in the previous Section. Figures 10 and 11 depict the phase voltage and current waveforms of D-STATCOM in capacitive mode (injection, Cap_mod) and inductive mode (absorption, Ind_mod) for the proposed strategy, PIAL, and PIPI strategy under scenario 1.

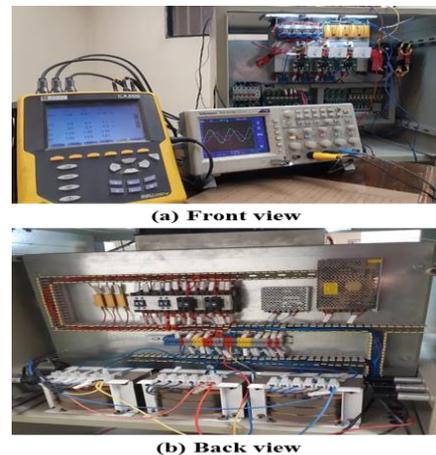


Fig. 9. Experimental Setup

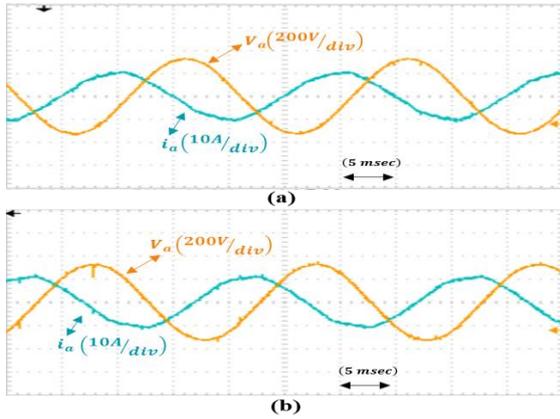


Fig. 10. Phase voltage (V_a) and phase current (i_a) under scenario 1 in Cap_mod: (a) PIAL; (b) PIPI

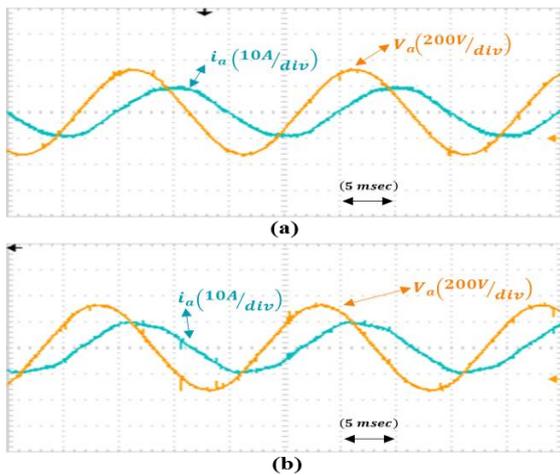


Fig. 11. Phase voltage (V_a) and phase current (i_a) under scenario 1 in Ind_mod: (a) PIAL; (b) PIPI

Since the parameters are considered in nominal condition under scenario 1, both PIAL and PIPI methods properly provide the demanding reactive current with low THD, indicated in Table 4.

Figures 12 and 13 show experimental results for the phase voltage and current waveforms of D-STATCOM under scenario 3 where -30% uncertainties in filter parameters. It is clear that the reactive current profile in Figs. 12 and 13 is deviated from a pure sinusoidal waveform compared with nominal condition, indicated in Figs. 10 and 11, when PIPI method is used as the control system. However, the reactive current waveform for PIAL method under scenario 3 show that the profile is deviated slightly and it is almost a sinusoidal waveform. Such effects can be clearly observed in the reactive current THD for both PIAL and PIPI method. As shown in Table 4, the proposed approach has a low better voltage THD than the PIPI approach under scenario 3; additionally, Table 5 shows the PIAL approach has a lower current THD than the conventional PI method which consistent with simulation results shown in Table 3 and Figs. 10-13.

Table 4. THD of pcc voltage under different control strategies

Controller	PIPI		PIAL	
	Cap.	Ind.	Cap.	Ind.
Scenario1	2.1%	2.2%	1.8%	1.7%
Scenario3	2.4%	2.6%	2.1%	2.2%

Table 5. THD of reactive current provided by D-STATCOM under different control strategies

Controller	PIPI		PIAL	
	Cap.	Ind.	Cap.	Ind.
Scenario1	3.8%	4.1%	4.1%	3.4%
Scenario3	5.7%	6.1%	4.1%	3.9%

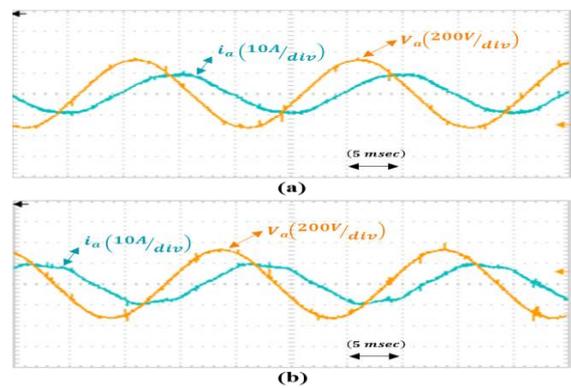


Fig. 12. Phase voltage (V_a) and phase current (i_a) under scenario 3 in Cap_mod: (a) PIAL; (b) PIPI

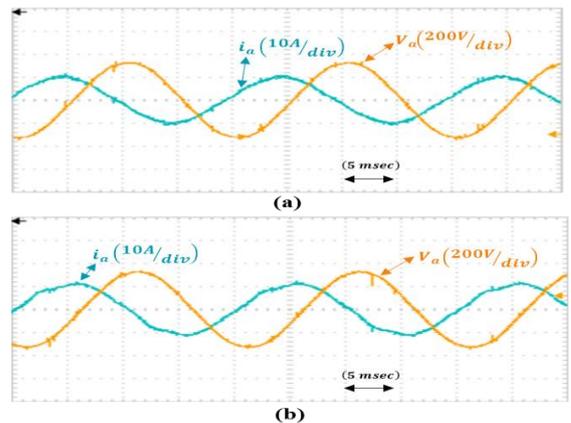


Fig. 13. Phase voltage (V_a) and phase current (i_a) under scenario 3 in Ind_mod: (a) PIAL; (b) PIPI

To analyze the behavior of both controller under sudden load changes, it is assumed that the load changes from the full inductive mode to full capacitive mode and vice versa for both scenario 1 and scenario 3.

Figures 14 and 15 show experimental results under scenario 1 in response to sudden load changes, and it is clear that the proposed PIAL approach has a faster response speed than the PIPI method because it rapidly estimates the instantaneous uncertainty forced on the system and uses such information to update the control law, while the PIPI one does not enjoy such an advantage.

In addition, the compensated reactive power by D-STATCOM using PIAL strategy has very low fluctuations while in PIPI strategy higher altitude fluctuations are seen in PIPI response.

As shown in Figs. 16 and 17, using the PIPI method leads to slower and more fluctuated response under scenario 3 whereas by using the proposed method, the system has a fast and acceptable response like scenario 1. This shows the proposed PIAL controller is a robust controller against parameter variation while the PIPI controller is sensitive against parameter uncertainties.

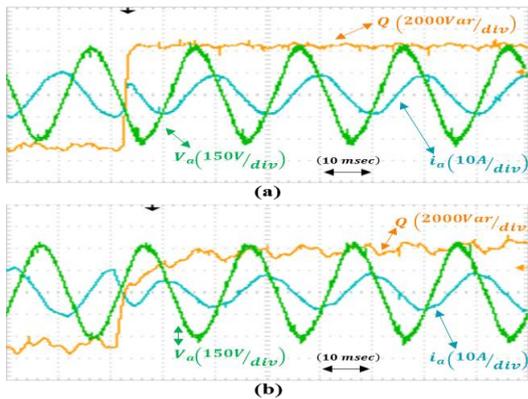


Fig. 14. Phase voltage (V_a), Compensated reactive power (Q), and phase current (i_a) under scenario 1 in Cap_mod: (a) PIAL; (b) PIPI

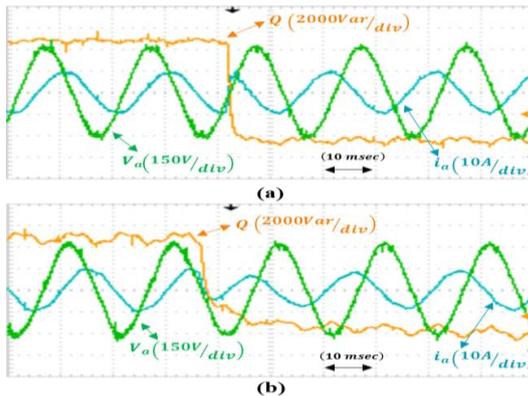


Fig. 15. Phase voltage (V_a), Compensated reactive power (Q), and phase current (i_a) under scenario 1 in Ind_mod: (a) PIAL; (b) PIPI

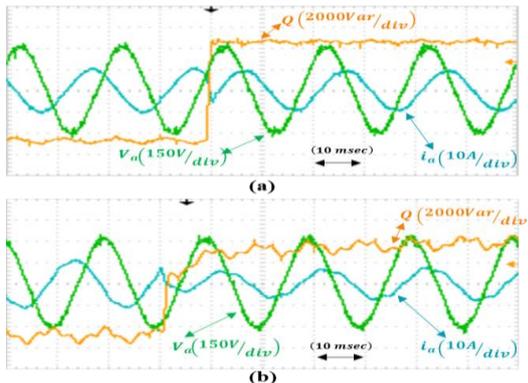


Fig. 16. Phase voltage (V_a), Compensated reactive power (Q), and phase current (i_a) under scenario 3 in Cap_mod: (a) PIAL; (b) PIPI

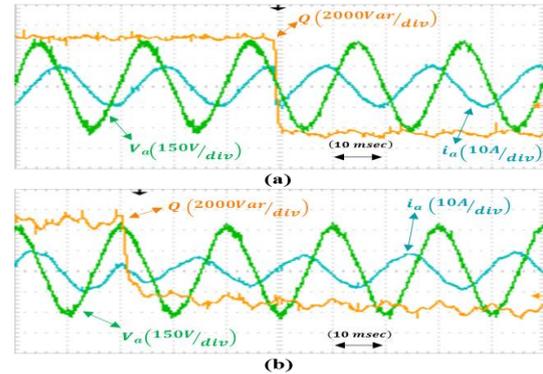


Fig. 17. Phase voltage (V_a), Compensated reactive power (Q) and phase current (i_a) under scenario 3 in inductive mode: (a) PIAL; (b) PIPI

6. Conclusion

This article suggest an adaptive controller for the inner loop of the cascaded control strategy that is used in a D-STATCOM control system. The proposed method does not need to a precise model of the D-STATCOM. Indeed this controller estimates the accurate model of the system based on a rough model. Therefore, it could properly adapt the control law based on the changes in the system and deviation in D-STATCOM parameter from nominal conditions. It is indicated that this controller has a robust response against presence of model and parameter uncertainties and sudden load changes. In addition, the simulation and experimental studies justified that the proposed method provides the advantages of constant switching frequency, low THD, and fast transient response. It is also shown that the adaptive control strategy has a better transient and steady performance than the conventional cascaded PI control method, especially under the presence of the uncertainties in the D-STATCOM's model and abrupt changes in operational regimes such as sudden load changes.

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