

Mitigation of Voltage Fluctuations Using Fuzzy-Based D-STATCOM in High Level Penetration of DG Systems

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ABSTRACT

Voltage fluctuations mainly resulting from variable output power of renewable energy sources; these are strictly challenging power quality in distribution-generation systems. The paper presents a control method for fuzzy based D-STATCOM to relieve variation of positive-sequence and negative-sequence voltages. D-STATCOM continuously operates as fundamental positive-sequence admittance and negative-sequence conductance to restore the positive-sequence voltage to the nominal value and negative-sequence voltage to the allowable level. At transient period both admittance and conductance are dynamically tuned to improve the voltage regulation performance. The ability of fuzzy logic to handle rough and unpredictable real world data made it suitable for a wide variety of applications, especially, when the models are too complex to be analyzed by classical methods. This paper presents the computer simulation of fuzzy based D-STATCOM under steady and transient state condition. The reduction of total harmonic distortions (THD) and voltage imbalance factor %VUF is discussed at all buses and maintained in acceptable level.

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1. INTRODUCTION

In The concept of micro-grid was proposed to coordinate various renewable energy sources (RESs) into distribution networks for both grid-connected and islanding operations. Increasing the use of RESs could help to relief network congestion; reduce system losses, and different infrastructure investments. These problems have received much attention recently, and numerous projects have developed by the functionality of micro grid. Conventionally, voltage fluctuations mainly resulting from impedance of transmission lines, uneven distribution of single-phase loads, and loading types. In the low voltage micro-grid system these scenarios become much severe due to reverse power flow provided by distributed generations (DGs) in either single or three-phase connection.

Voltage fluctuations cause the system losses, transformer overloading, capacity reduction and motor overheating, and even results in output limitation of DGs, and malfunction of sensitive equipment, nuisance tripping of protected devices. According to IEEE Std 1547.2-2008 [9], the limitation of voltage fluctuations are up to $\pm 5\%$ as RESs are paralleled to low-voltage systems. Voltage imbalance is measured by %Unbalance i.e %VUF kept below 2.0%–3.0% is acceptable for both utility and manufactures, where %VUF are defined as the ratio of the negative-sequence voltage to the positive sequence voltage, and percentage of maximum deviation from the average value, respectively. Therefore, in grid connected operation voltage regulation is absolutely needed to permit more DGs.

Voltage regulation in the power system could be accomplished by using an on-load tap changer (OLTC) or (SVC) a static VAR compensator at substations, and a switched capacitor on feeders. With the help of these called intelligent or optimal control on all devices, on the real-time base the voltage profile could be improved [6],[7]. The advancement of semiconductor technologies i.e voltage-source converter-based solutions, such as static synchronous compensator (STATCOM), distributed STATCOM (D-STATCOM), unified power flow controller (UPFC), and active power filter (APF), become possible in practical applications. In transmission system STATCOM technology has been extensively studied to regulate voltage by adjusting its reactive power into the power system, whereas UPFC was designed between two sub-stations to control real- and reactive-power flows. On the other hand, the combination of D-STATCOM and APF are suitable for harmonic compensation, harmonic damping, and reactive-power compensation.

Voltage regulation may suffer from imbalanced voltage or harmonic distortion, the regulation performance of the D-STATCOM can be improved by separately controlling the fundamental positive and negative-sequence currents. Proper control strategies corresponding to the control objectives are necessary in order to achieve efficient utilization of D-STATCOM [11]. Most of the controllers used for this device are based on the PI controller shown in figure 2. Although the PI controllers are simple and easy to design, their performance deteriorates when the system operating conditions vary widely and large disturbances occur. Unlike the PI controllers, fuzzy logic controllers (FLCs) [17] are capable of tolerating uncertainty and imprecision to a greater extent. So, they produce good results under changing operating conditions and uncertainties in system parameters.

2. D-STATCOM AND OPERATION PRINCIPLE

The basic configuration of D-STATCOM as shown in figure1, it consists of three-phase voltage source inverter using IGBT, DC voltage source and connected to the distribution line by coupling transformer. The D-STATCOM operates as fundamental positive-sequence admittance and negative-sequence conductance as given

$$i^* = Y_p^* \cdot E_f^+ + G_n^* \cdot E_f^- \quad (1)$$

Where i^* is the reference current, E_f^+ and E_f^- are the fundamental positive-sequence and fundamental negative-sequence voltage. Y_p^* and G_n^* are the fundamental positive-sequence admittance and negative-sequence conductance are defined variable control gains to furnish regulating positive-sequence voltage and suppressing imbalanced voltage.

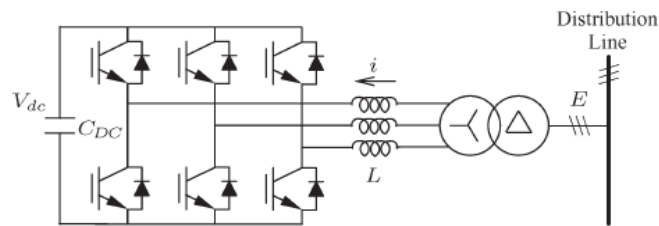


Figure 1. Power Circuit of D-STATCOM

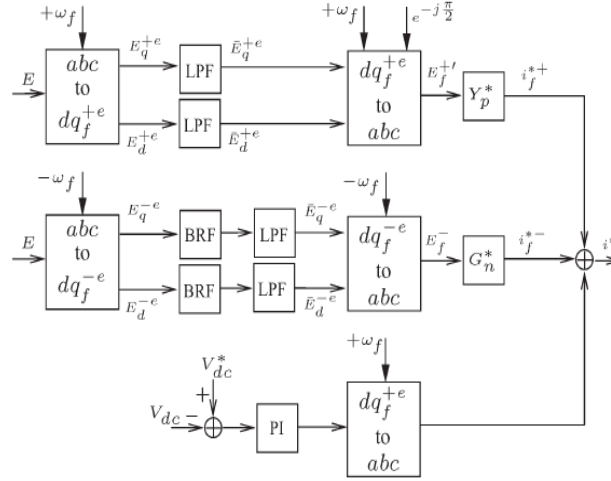


Figure 2. Generation of Reference Current

2.1. Generation of Reference-current

According to synchronous reference frame (SRF) transformation the control is actualized as shown in Figure 2.

By using low-pass filter (LPF) to filter out ripple components and the positive-sequence voltage E_{qd}^{+e} is obtained. The negative-sequence-voltage E_{qd}^{-e} is determined by the combination of LPF and a band rejected filter tuned at the second order frequency. From the Figure 2, the quadrature fundamental positive-sequence voltage E_f^+ and negative-sequence voltage E_f^- is available by applying reverse transformation. The positive-sequence current i_f^{*+} is equal to E_f^+ multiplied by Y_p^* and negative-sequence current i_f^{*-} are equal to E_f^- multiplied by G_n^* , respectively. Thus, the (1) is generated as a current command i^* . A dc voltage control is also designed for secure operation of the D-STATCOM. The fundamental current produced by the PI regulator which is in-phase with the positive-sequence voltage to maintain the dc voltage V_{dc} at the reference value V_{dc}^* .

2.2. Current Control

Figure 3. Shows a current regulator produces the voltage command v^* based on the current command i^* , the measured voltage E and measured current I for space vector pulse width modulation (PWM) control of the inverter. The transfer functions $H_h(s)$ and $H_f(s)$ as given as

$$H_f(s) = K_p + \frac{2K_{i,f}\xi\omega_f s}{s^2 + 2\xi\omega_f s + \omega_f^2} \quad (2)$$

$$H_h(s) = \sum_h \frac{2K_{i,h}\xi\omega_h s}{s^2 + 2\xi\omega_h s + \omega_h^2}$$

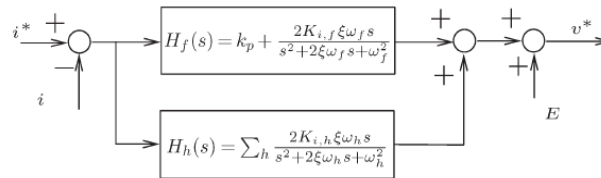


Figure 3. Current Control

Where $K_{i,f}$ and ω_f are the fundamental integral gain and its frequency, respectively; k_p represents a proportional gain; and ω_h and $K_{i,h}$ represent the harmonic frequency and its integral gain, respectively. The damping ratio ξ has tuned current regulator it introduce various narrow gain peaks at the harmonic

frequencies to reduce current distortion and a narrow gain peak centered at the fundamental frequency for fundamental current tracking systems. Figure 4, Shows the current-loop block diagram, in which PWM and digital signal processing delay are considered. T represents a sampling period. Further discussions on current control are provided in the simulation section.

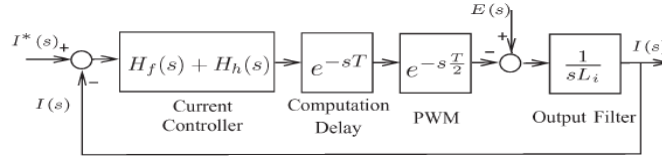


Figure 4. Current-Loop Block Diagram

2.3. Tuning Control

The tuning control of both G_n^* and Y_p^* as shown in figure 5. E_f^+ and E_f^- are defined as (3). By using LPF and SQRT operation they can approximately calculated, where LPF designed with cut-off frequency $\omega_c = 10$ HZ. Then, a PI regulator is actualize to generate Y_p^* to maintain E_f^+ at nominal value E_f^{+*} . Similarly by controlling of G_n^* the imbalanced voltage could be suppressed and maintained at an allowable level. The percentage of voltage unbalance factor (%VUF) is to estimate the level of imbalance voltage. %VUF is defined as the ratio of negative-sequence voltage to the positive-sequence voltage and as given as (4).

$$|E_f^+| = \sqrt{\frac{\int_t^{t+T} (E_q^{+e}(t)^2 + E_d^{+e}(t)^2) dt}{T}}$$

$$|E_f^-| = \sqrt{\frac{\int_t^{t+T} (E_q^{-e}(t)^2 + E_d^{-e}(t)^2) dt}{T}} \quad (3)$$

$$\%VUF = \frac{|E_f^-|}{|E_f^+|} \cdot 100\% \quad (4)$$

Basically, three control loops in the proposed system. The bandwidth of the current control loop, which depends on the switching frequency of the inverter. The current command is generated by the tuning of both admittance and conductance to improve the power quality. So their band widths are lower than that of current loop. To control both admittance and conductance by the tuning of PI parameters with suitable transient response and zero steady state error. Due to inverter losses the voltage on the dc capacitor will fluctuate and imbalanced voltage suppressed by conductance. Lower the dc capacitance, larger fluctuations will happen. Generally, the bandwidth of dc voltage control is lowest due to large capacitance in the system.

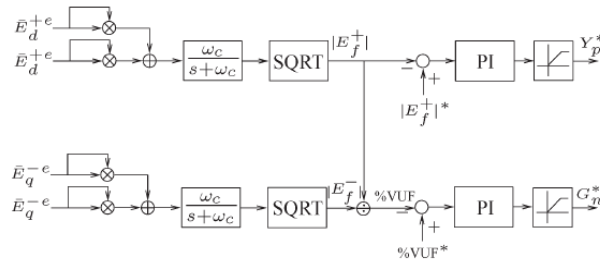


Figure 5. Tuning Control of Y_p^* and G_n^*

3. FUZZY LOGIC CONTROLLER (FLC)

The disadvantage of PI controller is its inability to react to sudden changes in the error signal, ϵ , because it is only capable of determining the arising value of the error signal without considering the change of the rise and fall of the error, which in mathematical terms, denoted as $\Delta\epsilon$. To solve this problem, Fuzzy

logic control as it is shown in Figure 6 is proposed. The determination of the output control signal, is done in an inference engine with a rule base having if-then rules in the form of

IF ε isAND $\Delta\varepsilon$ is, THEN output is.....

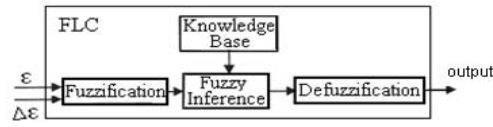


Figure 6. Basic Representation of the Fuzzy Logic Controller (FLC)

With the rule base, the value of the output is changed according to the value of the error signal ε , and the rate-of-error $\Delta\varepsilon$. The structure and determination of the rule base is done using trial-and-error methods [17] and is also done through experimentation. The MATLAB/SIMULINK model of fuzzy logic controller is shown in figure 7.

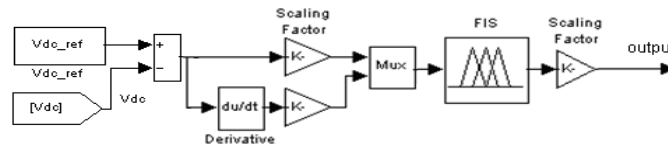


Figure 7. MATLAB/SIMULINK Model of Fuzzy Logic Controller.

4. SIMULATION STUDIES

A radial line as shown in figure 8, which is rated at 23 kv and 100MV, it is established by using alternate transient program to illustration of voltage fluctuations and verify the effectiveness of the D-STATCOM. At the end of radial line the grid voltage is sensitive to injection of both real and reactive power based on load flow analysis, therefore D-STATCOM installed at the end of the line. Table 1 and 2 are the line and load data, respectively.

The parameters of D-STATCOM given as follows.

- 1) Voltage base: 23kv, current base: 2510 A, and impedance base: 5.28 Ω .
- 2) PWM frequency: 10 kHz.
- 3) The reference fundamental positive-sequence voltage $|E^+_{f1}| = 1.0$ p.u. and voltage unbalance factor % VUF = 2.0%.
- 4) Current controller: $k_{i,h} = k_{i,f} = 40$ (for $h=5,7,11$ and 13), $k_p = 25$, and $\zeta = 0.001$.
- 5) Tuning controller: PI parameters for $|E^+_{f1}|$ ($k_p = 0.001$, $k_i = 1 \times 10^{-4}$) and for %VUF ($k_p = 10$ and $k_i = 0.05$).

Note that at the end of the bus inverter-based DG is to be installed and single-phase loads are connected between a and b phases to generate severe voltage variation as well as voltage imbalance. The PI regulator is controlling the power of DG it produce current command. But FLC is used in the D-STATCOM current control; to regulate the output current of the DG is realized by resonant current control. The control of the DG has already studied [8].

4.1. Steady-State Operation

Before starting of the D-STATCOM operation, the bus voltages are significantly swelled and imbalanced due to single-phase loads and DG as shown in Figure 9(b). At the end of the line, the voltage fluctuations are worse condition. For example at Bus 5, $|E^+_{f1}| = 1.06$ p.u. and %VUF = 5.1%. Table 3 shows corresponding $|E^+_{f1}|$ and %VUF for all buses. When the fuzzy based D-STATCOM is initiated with compensation of the positive-sequence voltage only ($G^*_n = 0$), then Table 4 shows the $|E^+_{f1}|$ on each bus could be restored to the nominal value. At this time, the D-STATCOM is operated at $Y^*_p = 0.37$ p.u. with rms currents $i_a = i_b = i_c = 0.37$ p.u. However, the voltage fluctuation is still significant as shown in figure 9(c) due to imbalanced voltage. After imbalance suppression is activated, the bus voltages are clearly recovered from

fluctuation as shown in figure 9(d). The corresponding all buses of both $|E^+_f|$ and %VUF could be maintained below the presetting level (1.0 p.u. and 2%), which illustrates on Table 5. As shown in Figure 9(g), the D-STATCOM consumes imbalanced currents $i_a = 0.52$ p.u., $i_b = 0.25$ p.u., and $i_c = 0.35$ p.u. with $G_n^* = 9.6$ p.u. and $Y_p^* = 0.37$ p.u., respectively. The total harmonic distortions are as follows THDa = 1.5%, THDb = 1.25%, THDc = 1.85%.

4.2. Transient Operation

The transient performance of the fuzzy based D-STATCOM is defined in Table 6. The transient behavior of the positive-sequence voltage $|E^+_f|$ and voltage unbalanced factor %VUF is shown in figure 10. while Y_p^* and G_n^* as shown in figure 11. When $t = 4$ and 6 s, three-phase loads at bus 3 and 4 are turned off, respectively, $|E^+_f|$ is increased. The tuning control of Y_p^* is correspondingly increased to maintain $|E^+_f|$ at 1.0 p.u. At $t = 7$ s, the single-phase loads are tuning off it reduces the imbalanced voltage as shown in figure 10 (b). So G_n^* is decreased to maintain %VUF at 2%, as shown in figure 11(b).

The output power of DG decreases from 0.9 to 0.45 p.u at $t = 8$ s. Y_p^* and the required reactive power of the D-STATCOM are reduced, due to swelled voltage becomes slighter. More interestingly, at $t = 9$ s the DG being turned off then $|E^+_f|$ becomes lower than 1.0 p.u. In these condition, the fuzzy based D-STATCOM operates with reduced Y_p^* for increasing voltage.

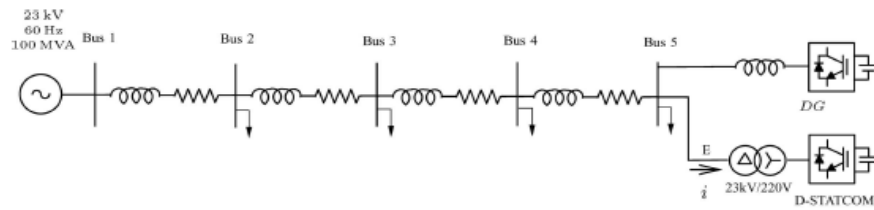


Figure 8. Simulation Circuit

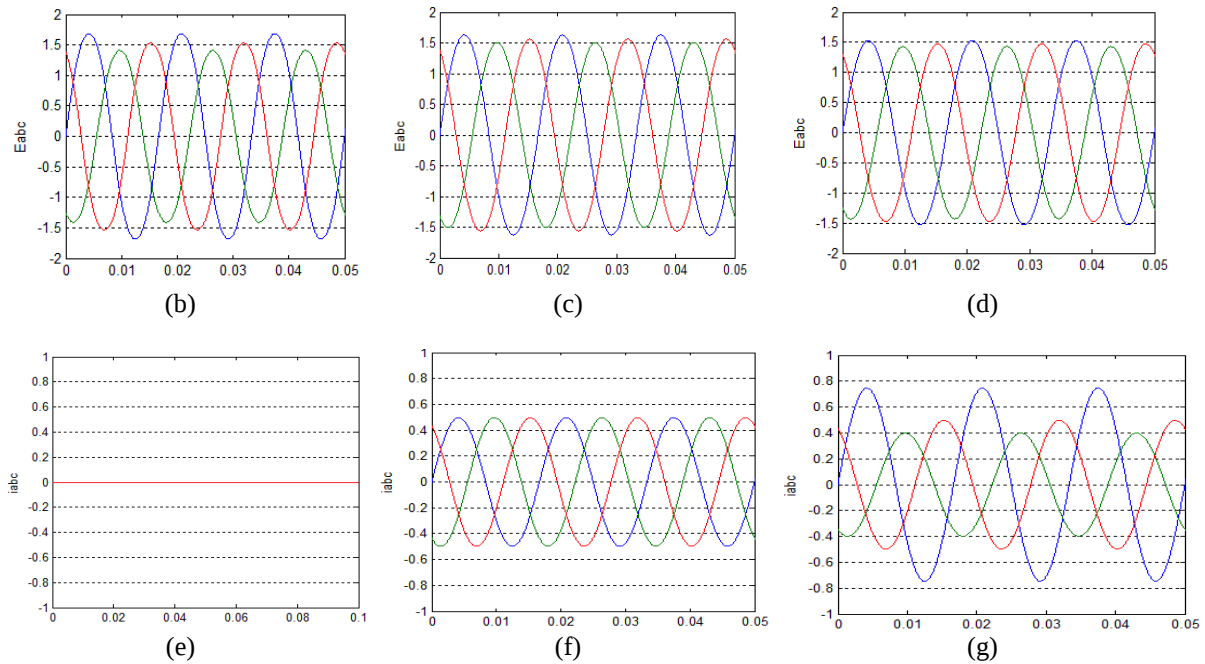


Figure 9. Test results (b) D-STATCOM off. (c) D-STATCOM on, but $G_n^* = 0$. (d) D-STATCOM on. (e) D-STATCOM off. (f) D-STATCOM on, but $G_n^* = 0$. (g) D-STATCOM on.

Table 1. Line Data (in per unit)

Line segment	R	X
Bus 1-2	0.030	0.033
Bus 2-3	0.049	0.049
Bus 3-4	0.034	0.039
Bus 4-5	0.021	0.030

Table 2. Load Data (in per unit)

Bus	3Ø P	3Ø Q	3Ø rectifier	3Ø DG	1Ø P
2	0.052	0.032			0.106 _{ab}
3	0.051	0.024			0.106 _{ab}
4	0.003	0.017	0.092		0.106 _{ab}
5	0.014	0.007		0.9	0.106 _{ab}

Table 3. Bus Voltages after D-STATCOM only Compensates Positive-Sequence Voltages

	BUS 2	BUS 3	BUS 4	BUS 5
$ E_f^+ $	1.00	1.02	1.04	1.06
%VUF	1.8%	3.7%	4.8%	5.1%

Table 4. Bus Voltages Before The D-STATCOM is Started

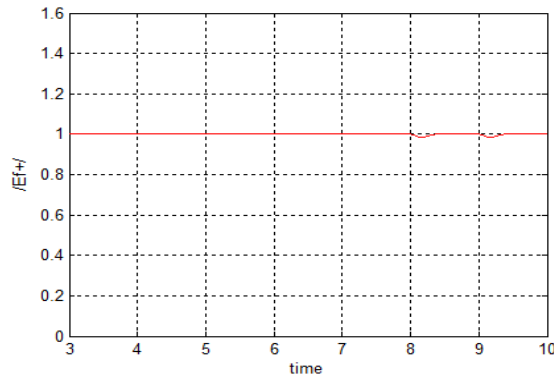
	BUS 2	BUS 3	BUS 4	BUS 5
$ E_f^+ $	1.00	1.00	1.00	1.00
%VUF	1.8%	3.7%	4.8%	5.1%

Table 5. Bus Voltages After the D-STATCOM Compensates Both Positive and Negative-Sequence Voltages

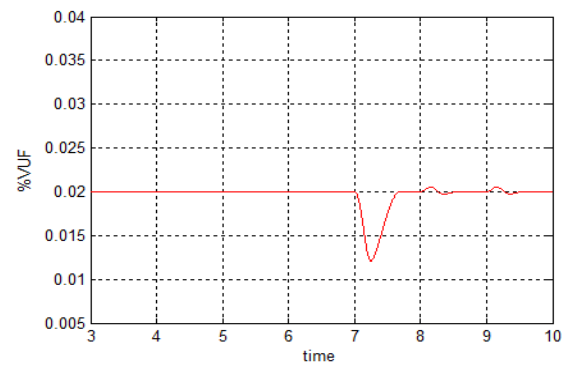
	BUS 2	BUS 3	BUS 4	BUS 5
$ E_f^+ $	1.00	1.00	1.00	1.00
%VUF	1.7%	1.9%	2.0%	2.0%

Table 6. Load OR DG Variation

t	Event	Location
4	3Øload off	Bus 3
6	3Øload off	Bus 4
7	1Øload off	Bus 4
8	DG output from 0.9to 0.45 p.u.	Bus 5
9	DG output from 0.45to 0 p.u.	Bus 5



(a)



(b)

Figure 10. Voltages in Transient Operation, (a) $|E_f^+|$. (b) %VUF.

Therefore, the voltage regulation could be sophisticated by dynamically tuning Y_p^* and G_n^* of the fuzzy based D-STATCOM. From the above simulations, it is clear and obvious that the proposed fuzzy controller is able to control the DC-bus voltage efficiently in steady or transient state.

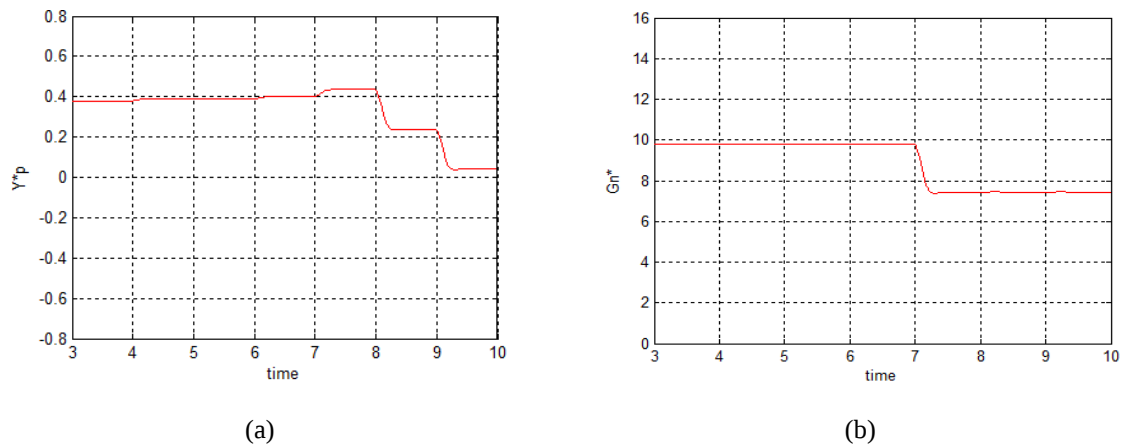


Figure 11. D-STATCOM Commands in Transient Operation. (a) Y_p^* . (b) G_n^* .

5. CONCLUSION

The paper has presented the alleviation of voltage fluctuations at steady state and transient state based on fuzzy logic control method of D-STATCOM in high level penetration of DG systems. Together with positive-sequence admittance to recover the positive-sequence voltage, negative sequence conductance is implemented to cooperatively improve imbalanced voltage. A tuning control is designed to dynamically adjust admittance as well as conductance commands to maintain both positive and negative-sequence voltages at an allowable level in response to power variation of DGs or loads. The reduction of total harmonic distortions (THD) and percentage of unbalance factor (%VUF) maintained at all buses in an acceptable levels. One of the major advantages of this scheme is being less sensitive to the system parameters variation; in addition, it is characterized by a negligible response time. Simulation results analysis has shown that the proposed controller has fast dynamic response, high accuracy of tracking the DC-voltage reference, and strong robustness to load sudden variations.

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