

Mitigation of Voltage Fluctuations at Transient Period using D-STATCOM in High Level Penetration of Distribution-Generation 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 control method for 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. A controlling of fundamental current of the D-STATCOM and reduction of harmonic current is accomplished by the proportional-resonant current regulator with selective harmonic compensation. The voltage imbalance factor %VUF is discussed at all buses and maintained in acceptable level . The paper presents the computer simulation of D-STATCOM with transient period of distribution-generation system.

Index Terms—D-STACOM (Distributed-static compensator), voltage imbalance, voltage fluctuations, micro-grid.

1. INTRODUCTION

The concept of micro-grid was proposed to coordinate various renewable energy sources (RESs) into distribution networks for both grid-connected and islanding operations [1], [2]. 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 [3].

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 [4], 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 [5]. 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 [8]–[10]. 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 [12].

2. D-STATCOM AND ITS OPERATION PRINCIPLE

The basic configuration of D-STATCOM as shown in fig.1, 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

$$i^* = Y_p^* \cdot E_{f^+} + G_n^* \cdot E_{f^-} \quad \text{----- (1)}$$

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.

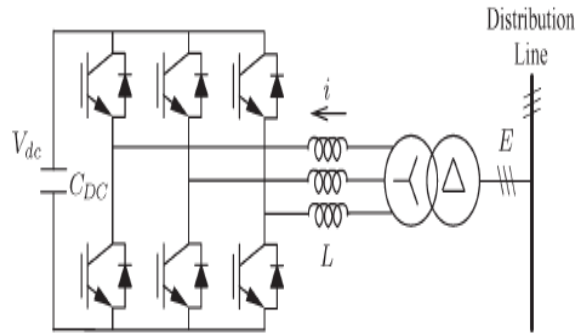


Fig.1. Power circuit of D-STATCOM

1. Generation of Reference-current

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

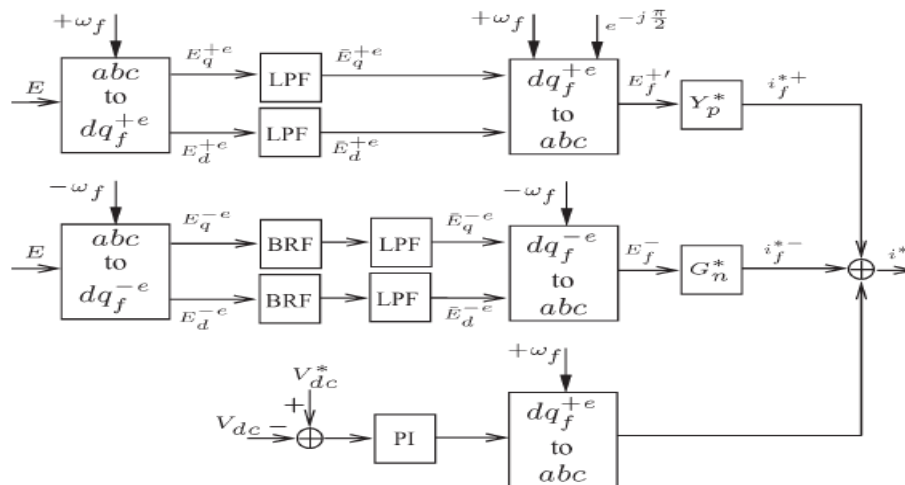


Fig.2. Generation of reference current.

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 Fig.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. Current Control

Fig.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

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

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

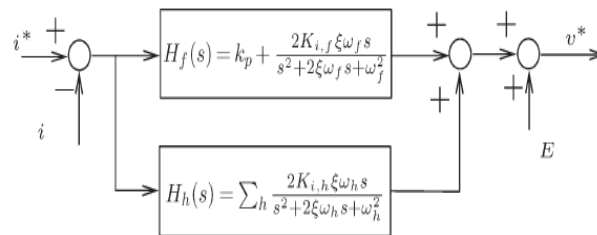


Fig.3. Current Control

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. Fig. 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.

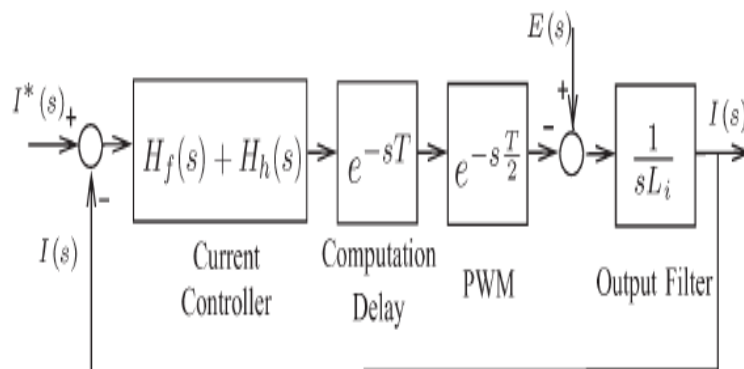


Fig.4. Current-loop block diagram.

3. Tuning Control

The tuning control of both G_n^* and Y_p^* as shown in fig.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 ad the ratio of negative-sequence voltage to the positive-sequence voltage and as given as (4).

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

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

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

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 loses 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.

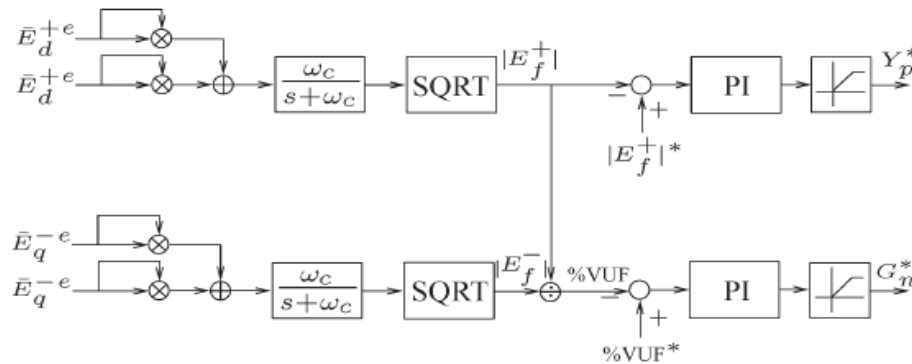


Fig.5. Tuning control of Y_p^* and G_n^*

3. SIMULATION STUDIES

A radial line as shown in fig.6. 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 [17], therefore D-STATCOM installed at the end of the line. Table I and II 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 $|E_f^+| = 1.0$ 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 $\xi = 0.001$.
- 5) Tuning controller: PI parameters for $|E_f^+|$ ($k_p = 0.001$, $k_i = 1 \cdot 10^{-4}$) 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 sever voltage variation as well as voltage imbalance. The PI regulator is controlling the power of DG it produce current command. Similar to 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 [16].

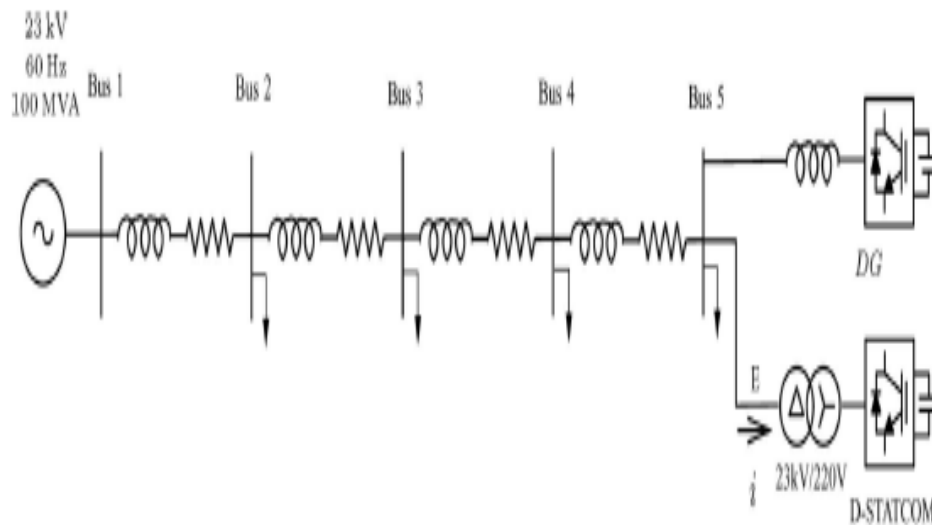


Fig.6. Simulation circuit.

TABLE I Line data (in per unit)

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

TABLE II Load data (in per unit)

Bus	3 \emptyset P	3 \emptyset Q	3 \emptyset rectifier	3 \emptyset DG	1 \emptyset 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}

A. 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 Fig.7 (b). At the end of the line, the voltage fluctuations are worse condition. For example at Bus 5, $|E_f^+| = 1.06$ p.u. and %VUF = 5.1% . Table III shows corresponding $|E_f^+|$ and %VUF for all buses. When the D-STATCOM is initiated with compensation of the positive-sequence voltage only ($G_n^* = 0$), then Table IV shows the $|E_f^+|$ 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 fig.7(c) due to imbalanced voltage. After imbalance suppression is activated, the bus voltages are clearly recovered from fluctuation as shown in fig.7 (d). The corresponding all buses of $|E_f^+|$ and %VUF could be maintained below the presetting level (1.0 p.u. and 2%), which illustrates on Table V. As shown in Fig.7 (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.

TABLE III Bus Voltages before the D-STATCOM is Started

	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 IV

Bus Voltages after the D-STATCOM Only Compensates Positive-sequence Voltage

	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 V

Bus Voltages after the D-STATCOM Compensates Voltages both positive and negative-sequence

	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%

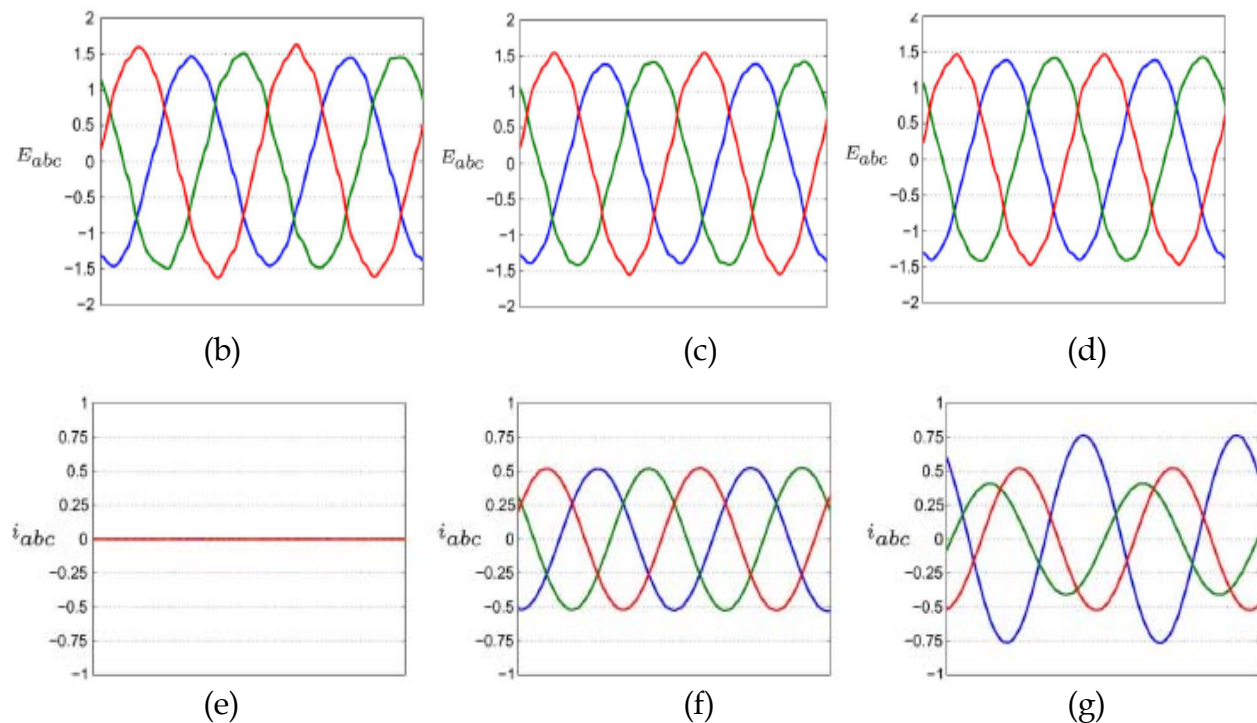


Fig.7. Test results (b)D-STATCOM off. (c) D-STATCOM on, but $G_n^* = 0$. (d) D-STATCOM on. (e) D-STATCOM off. (f) D-STATCOM on, but $G_n^* = 0$. (g) D-STATCOM on.

B. Frequency-Domain Analysis

The current control frequency responses of the open and closed-loop gains as shown in fig.8. At the fundamental frequency the fundamental current-tracking capability is assured by a resonant gain. To reduce the harmonic current at various narrow gains (5th, 7th, 11th and 13th frequencies). The fig.7 (g) shows the D-STATCOM currents are almost maintains as a sinusoidal waveforms. These are the conformation of harmonic reduction because at Bus 4 the nonlinear load results the severely distorted line voltages. The total harmonic distortions are as follows $THD_a = 3\%$, $THD_b = 2.5\%$, $THD_c = 3.7\%$.

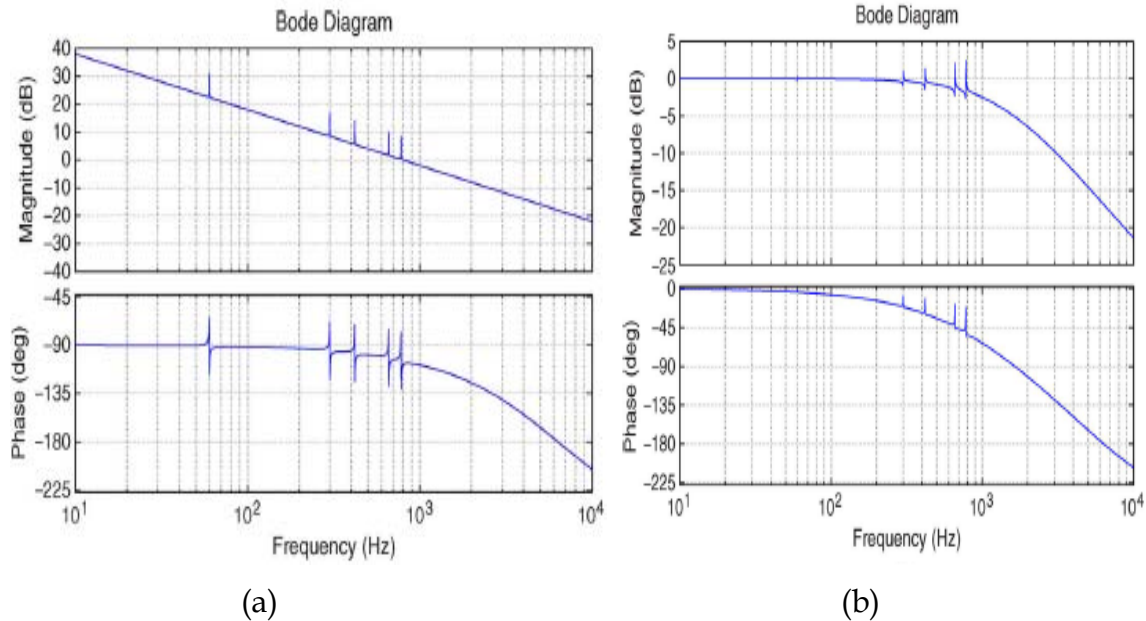


Fig.8. Frequency-domain analysis of the current loop. (a) Open loop. (b) Closed loop

C. Transient Operation

The transient performance of the D-STATCOM is defined in Table VI. The transient behavior of the positive-sequence voltage $|E_f^+|$ and voltage unbalanced factor %VUF is shown in fig.9.while Y_p^* and G_n^* as shown in fig.10. When $t = 4$ and 6 s, three-phase loads at bus 3 and 4 are turned off, respectively, $|E_f^+|$ is increased.

TABLE VI Load OR DG variation

t	event	location
4	3 \emptyset load off	Bus 3
6	3 \emptyset load off	Bus 4
7	1 \emptyset load off	Bus 4
8	DG output from 0.9 p.u. to 0.45 p.u.	Bus 5
9	DG output from 0.45 p.u. to 0 p.u.	Bus 5

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 fig.9 (b). So G_n^* is decreased to maintain %VUF at 2%, as shown in fig.10 (b).

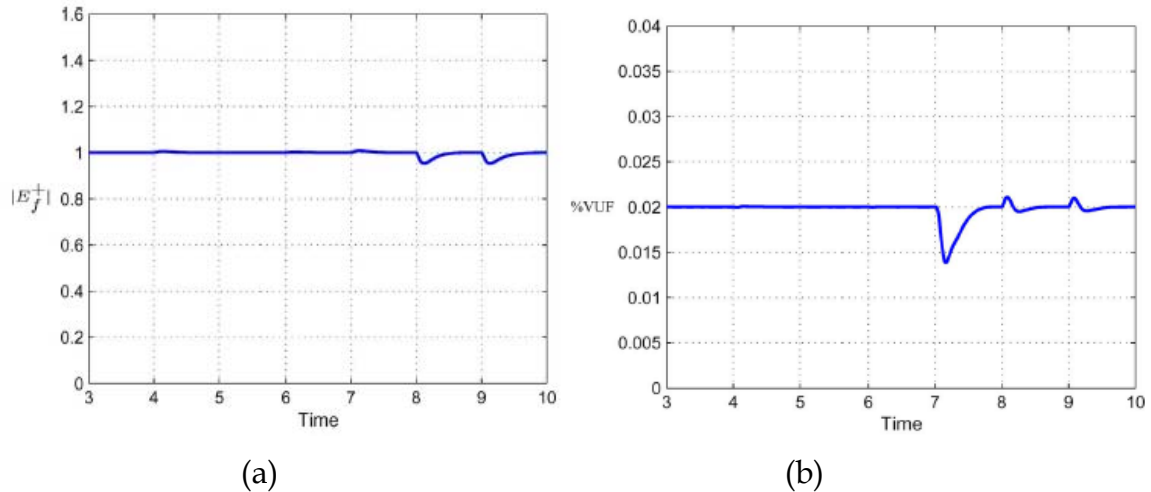


Fig.9. Voltages in transient operation, (a) $|E_f^+|$. (b) %VUF.

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 D-STATCOM operates with minus Y_p^* to supply reactive current for increasing voltage.

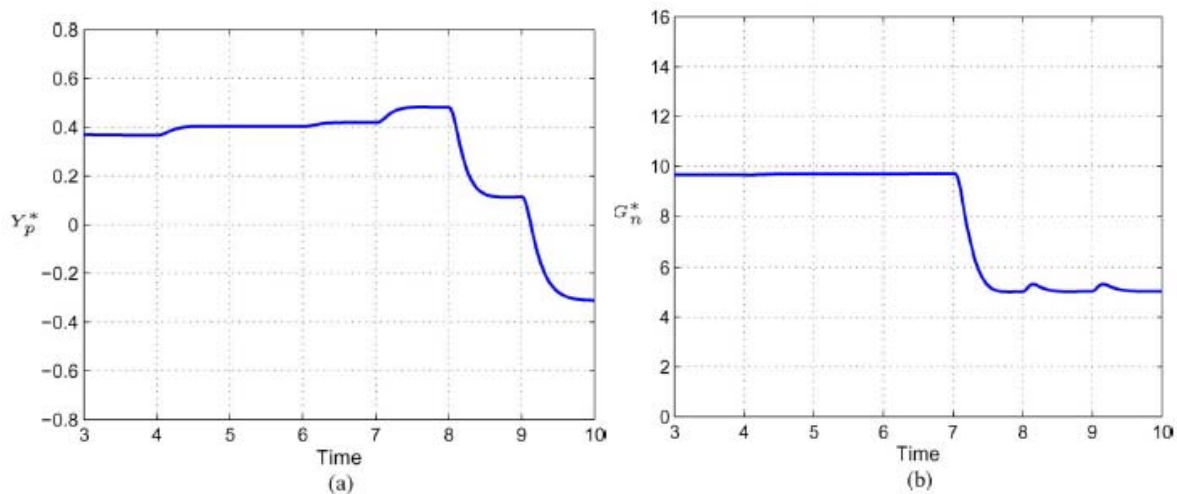


Fig .10. D-STATCOM commands in transient operation. (a) Y_p^* . (b) G_n^* .

In this position instead of an inductor, the D-STATCOM currently behaves as a capacitor. Therefore, the voltage regulation could be sophisticated by dynamically tuning Y_p^* and G_n^* of the D-STATCOM.

D. Large R/L Ratio

The R/L ratio is high in the low voltage system. In case, the R/L ratio increased by two and five times the D-STATCOM performance as shown in Table VI and VII. Here, $|E_f^+|$ and %VUF are increased towards worse with increase of R/L ratio. After D-STATCOM Starts operation, $|E_f^+|$ is restored to the nominal values and %VUF is also improved. However, at buses 3 and 4 imbalanced voltages are still higher than 2% because the feeder with high R/L ratio. The D-STATCOM currents are $i_a= 0.75$ p.u., $i_b= 0.43$ p.u., and $i_c= 0.57$ p.u. for Table VII and $i_a= 0.90$ p.u., $i_b= 0.54$ p.u., and $i_c= 0.80$ p.u. for Table VIII. Obviously, the D-STATCOM needs larger currents to realize voltage regulation compared with the results.

TABLE VII R/L Ratio Increased By Two times

		BUS 2	BUS 3	BUS 4	BUS 5
D-STATCOM OFF	$ E_f^+ $	1.00	1.04	1.07	1.10
D-STATCOM OFF	%VUF	2.5%	5.4%	6.9%	7.3%
D-STATCOM ON	$ E_f^+ $	1.00	1.00	1.00	1.00
D-STATCOM ON	%VUF	1.4%	2.2%	2.4%	2.0%

TABLE VIII R/L Ratio Increased By Five times

		BUS 2	BUS 3	BUS 4	BUS 5
D-STATCOM OFF	$ E_f^+ $	1.02	1.09	1.17	1.25
D-STATCOM OFF	%VUF	4.8%	10%	13%	14%
D-STATCOM ON	$ E_f^+ $	1.00	1.00	1.00	1.00
D-STATCOM ON	%VUF	2.4%	3.8%	3.2%	2.0%

4. CONCLUSION

The paper has presented the alleviation of voltage fluctuations at transient period using a 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 percentage of unbalance factor (%VUF) maintained at all buses in an acceptable levels.

REFERENCES

- [1] R. Lasseter, "Microgrids," in Proc. IEEE Power Eng. Soc. Winter Meeting, 2002, pp. 305–308.
- [2] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management," IEEE Power Energy Mag., vol. 6, no. 3, pp. 54–65, May/June. 2008.
- [3] C. L. Masters, "Voltage rise: The big issue when connecting embedded generation to long 11 kV overhead lines," Inst. Elect. Eng. Power Eng. J., vol. 16, no. 1, pp. 5–12, Feb. 2002.
- [4] IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE Std. 1547.2-2008,
- [5] A. V. Jouanne and B. Banerjee, "Assessment of voltage unbalance," IEEE Trans. Power Del., vol. 16, no. 4, pp. 782–790, Oct. 2001.
- [6] T. Senjyu, Y. Miyazato, A. Yona, N. Urasaki, and T. Funabashi, "Optimal distribution voltage control and coordination with distributed generation," IEEE Trans. Power Del., vol. 23, no. 2, pp. 1236–1242, Apr. 2008.
- [7] D. Westermann and M. Kratz, "A real-time development platform for the next generation of power system control functions," IEEE Trans. Ind. Electron., vol. 57, no. 4, pp. 1159–1166, Apr. 2010.
- [8] L. Gyugyi, "A unified power flow control concept for flexible ac transmission systems," Proc. Inst. Elect. Eng., vol. 139, no. 4, pp. 323–331, Jul. 1992.
- [9] N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. New York: Wiley, 999.
- [10] R. Gupta, A. Ghosh, and A. Joshi, "Multiband hysteresis modulation and switching characterization for sliding-mode-controlled cascaded multilevel inverter," IEEE Trans. Ind. Electron., vol. 57, no. 7, pp. 2344–2353, Jul. 2010.
- [11] P. S. Sensarma, K. R. Padiyar, and V. Ramanarayanan, "Analysis and performance evaluation of a distribution STATCOM for compensating voltage fluctuations," IEEE Trans. Power Del., vol. 16, no. 2, pp. 259–264, Apr. 2001.
- [12] E. Twining, M. J. Newman, P. C. Loh, and D. G. Holmes, "Voltage compensation in weak distribution networks using a D-STATCOM," in Proc. IEEE PEDS, 2003, pp. 178–183.
- [13] T.-L. Lee and P.-T. Cheng, "Design of a new cooperative harmonic filtering strategy for distributed generation interface converters in an islanding network," IEEE Trans. Power Electron., vol. 42, no. 5, pp. 1301–1309, Sep. 2007.

- [14] T.-L. Lee, S.-H. Hu, and Y.-H. Chan, "Design of D-STATCOM for voltage regulation in microgrids," in Proc. IEEE Energy Convers. Congr. Expo. 2010, pp. 3456–3463.
- [15] D. N. Zmood and D. G. Holmes, "Stationary frame current regulation of PWM inverters with zero steady-state error," IEEE Trans. Power Electron., vol. 18, no. 3, pp. 814–822, May 2003.
- [16] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1398–1409, Oct. 2006.
- [17] E. Demirok, D. Sera, R. Teodorescu, P. Rodriguez, and U. Borup, "Evaluation of the voltage support strategies for the low voltage grid connected PV generators," in Proc. IEEE Energy Convers. Congr. Expo, 2010, pp. 710–717.