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# Design and installation of a ±250 kVAr D-STATCOM for a distribution substation

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**Abstract**

A Static Compensator (STATCOM) is a flexible ac transmission system (FACTS) controller, which can either absorb or deliver reactive power to a power system. This technology has resulted in an equipment that is principally different from conventional static VAr compensators (SVC). The steady-state characteristics of a STATCOM are similar to those of a rotating synchronous condenser. A ±250 kVAr D-STATCOM was designed and installed for a 1.6 MVA distribution substation in Tehran, which is the first installation of this type in Iran. The principal aim of this installation is reactive power control for voltage regulation, with a particular work on reduction of unbalance issue. This paper describes the design and operating fundamentals and characteristics of a D-STATCOM as well as its basic control strategy. Moreover, different practical results demonstrate the flexible operation of the employed equipment.


*Keywords:* FACTS; D-STATCOM; Reactive power; Compensation; Voltage regulation

## 1. Introduction

The use of flexible ac transmission system (FACTS) controllers can overcome disadvantages of electromechanically controlled transmission systems. The Static Compensator (STATCOM) is a static synchronous generator employed as a parallel device static VAr compensator (SVC) in ac power systems [1–3]. The amplitude and angle of its capacitive or inductive output current can be controlled independent of the ac applied voltage [4]. This paper describes the application of new technologies to a ±250 kVAr prototype installation, and provides an outline of the development work associated with it. Fig. 1(a) shows the PWM controlled LCL D-STATCOM, consisting of a voltage source inverter connected to the distribution system through a LCL passive filter. This improves the harmonic performance compared to the more commonly used simple inductive filter. Various electronic cards are used by the control unit of the D-STATCOM, including the sampling circuit, digital transmitter card, PWM board, protection system, phase locked loop (PLL), zero voltage detector (ZVD), and the digital signal processor (DSP) as shown by Fig. 2.

## 2. D-STATCOM operating principles

Considering Fig. 1(a), suppose both the ac system voltage $V_s$ and the converter-composed voltage $V_C$ are in phase. By varying $V_C$, reactive power can be controlled to emulate a certain application such as voltage regulation. However, for stable operation of D-STATCOM, the converter output has a small phase difference with the ac system voltage ($\alpha$) for managing the D-STATCOM power losses. In [1–3], the explained mode of operation is modelled by transforming the system to a synchronous frame. Then, the resulting state space model is analyzed, showing a stable system with oscillatory dynamic response for D-STATCOM. A typical steady-state operation of D-STATCOM as a function of $\alpha$ is depicted in

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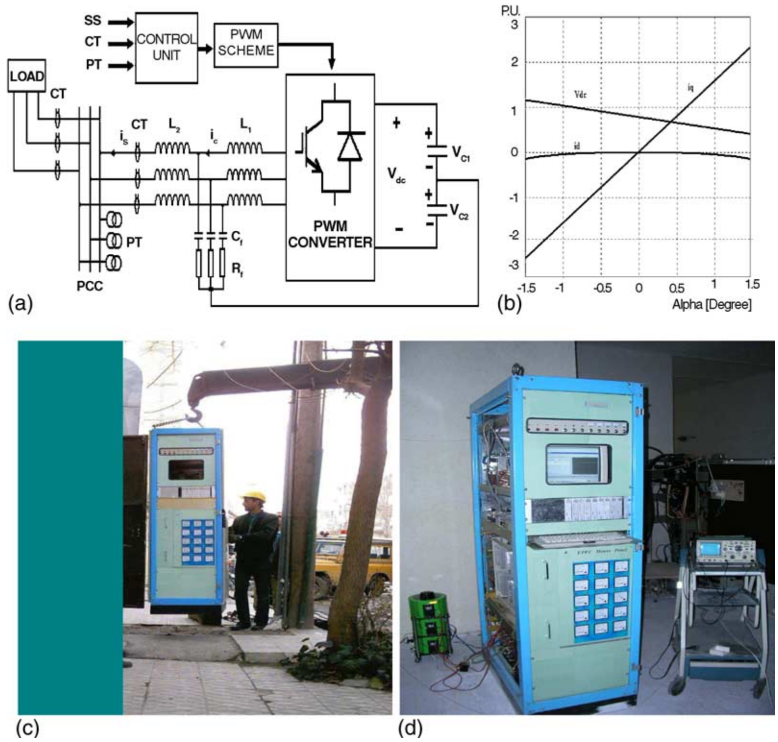


Fig. 1. (a) Single-line diagram of D-STATCOM; (b) dq currents ($i_d$ and $i_q$) of D-STATCOM together with capacitor dc voltage ($V_{dc}$) as three linear functions of $\alpha$; (c) transferring the D-STATCOM inside the Khoshnoodi substation for installation; (d) the designed D-STATCOM under practical tests.

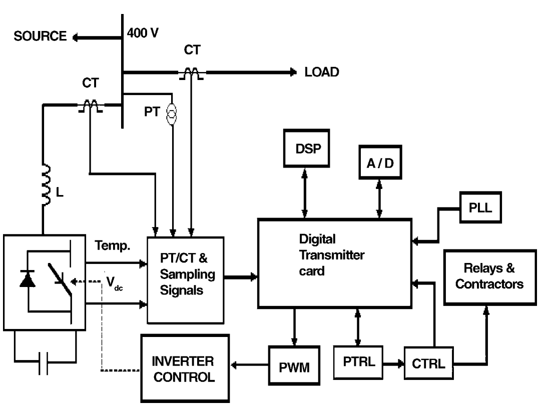


Fig. 2. Single-line schematic diagram of the control unit of D-STATCOM.

Fig. 1(b). Three state variables, $i_d$, $i_q$, and $V_{dc}$, give the equivalent active current, reactive current, and the dc voltage, respectively. This figure shows almost a linear relationship for $i_q$ as a function of $\alpha$ typically over $[-1.5°, 1.5°]$, although the state equations represent a non-linear system. This suggests a way of controlling D-STATCOM, mainly by $\alpha$.

## 3. Prototype installation

This prototype D-STATCOM is rated for ±250 kVAr, employing an angle control strategy described in [2], and was installed at the Khoshnoodi substation in August 2003. Fig. 1(c and d) shows installation of the device.

### 3.1. Application background

The substation of Khoshnoodi is situated in Tehran distribution system, and connected to three other substations, Keyhan, Ghadimi, and Pirouzi. Fig. 3 shows a one-line diagram of the local distribution system in which three named substations are connected to Khoshnoodi. It serves a big area including eight feeders of both industrial and residential customers. The transformer $T_1$ is rated for 1.6 MVA, and steps down 20 kV to 400 V. This substation was selected for the D-STATCOM installation for the following reasons:

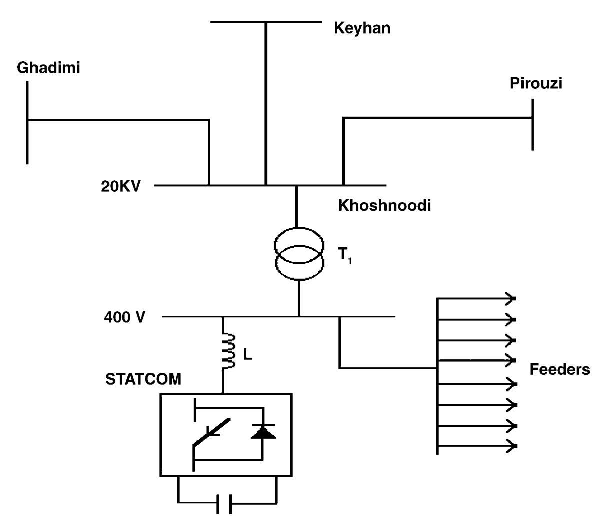


Fig. 3. Single-line diagram of the local distribution network under study.

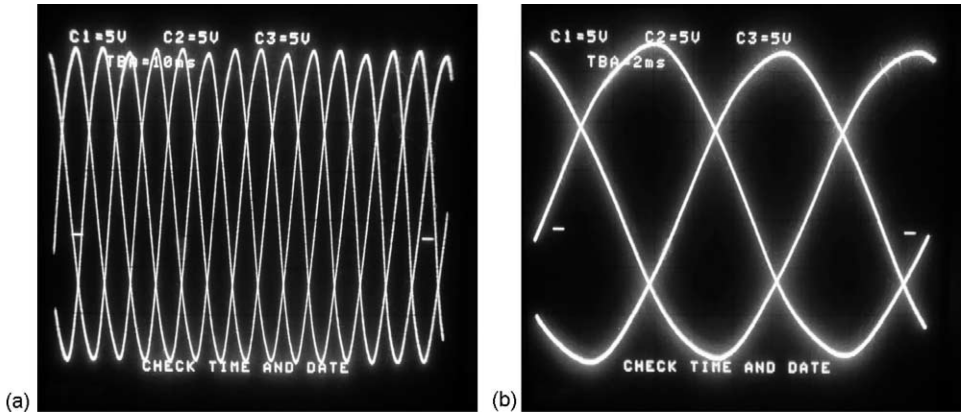


Fig. 4. Typical light load voltage unbalances at Khoshnoodi substation.

- Consider $R + \mathrm{j}X$ is the Thévenin equivalent impedance of a distribution system. When $\frac{X}{R}$ ratio is relatively high, then imaginary part of total voltage drop as well as the voltage variations due to active power variations are ignored. This eventually simplifies the voltage regulation as a linear function of reactive power. However, both the imaginary part of the voltage drop and active power variations can be taken into account for relatively small $\frac{X}{R}$ ratio of the long distance cables. For either case, as demand increases on these systems, power quality issues such as poor voltage regulation become a significant problem.

The Khoshnoodi's 400 V bus experiences voltage rise during light load conditions, and voltage drop during peak load conditions. Under balanced condition, the rated current and apparent power of Khoshnoodi substation are 2.50 kA and 1.6 MVA, respectively, and its short circuit power $S_{\mathrm{sc}}$ is equal to 3.4 MVA. Electrical companies in Iran are basically used to follow the IEC rules on voltage regulation (slightly different). Here, the *normal* percent voltage regulation $\left(\frac{\Delta V}{V}\%\right)$ is limited to $[-2.5\%, 2.5\%]$, the *abnormal* to $[-10\%, 5\%]$, and beyond this latter is called *unusual* operating practice [5]. Using the reactive power theory [6], any voltage variations beyond the normal standard practice can be compensated such that $\frac{\Delta V}{V}\%$ is maintained within the normal region. At the same time, a 10% change in $\frac{\Delta V}{V}\%$ corresponds to 340 kVAr reactive power. Thus, to manage the voltage change within the normal region, D-STATCOM should be capable of producing $Q_{\mathrm{C}}$ as follows:

$$Q_{\mathrm{C}} = 340 - S_{\mathrm{sc}}\frac{\Delta V}{V}\% \quad (1)$$

where substituting $\frac{\Delta V}{V} = 2.5\%$ in (1) will result in a maximum reactive power $Q_{\mathrm{C}} = 250$ kVAr needed for voltage regulation. Therefore, a ±250 kVAr D-STATCOM keeps the voltage variations within the permissible region by compensating about 7.5% voltage regulation in the worst case.

- In practice, the grid source is *not* always balanced. Unbalance conditions on a distribution three-phase bus are unavoidable because single-phase loads are allocated unevenly to the phases. A D-STATCOM works perfectly as long as the applied voltages are balanced. Recently, operation of D-STATCOM under unbalanced supply has been studied, which indicates that the dc capacitor voltage oscillates dominantly at twice the synchronous frequency (e.g. [7]). This will then make waveforms distorted by introducing low-order harmonics to the inverter output voltages and currents. These issues have also been confirmed by practical results presented in [7,8].

The Khoshnoodi substation also operates under unbalanced conditions. The voltage unbalance can be calculated and expressed using different standard rules. These definitions may give different results though. However, the IEEE standard 1159 gives similar results compared to other standards such as the National Electric Manufacturers Association (NEMA) [9]. Fig. 4 shows unbalanced voltages of Khoshnoodi substation, as two examples, under typical light load operating conditions. For Fig. 4(a), unbalanced magnitudes and phase angles were accurately calculated by MATLAB as $(\|v_a\|, \|v_b\|, \|v_c\|) = (236, 234, 237)$ V and $(\angle v_a, \angle v_b, \angle v_c) = (0°, -121°, 119.45°)$. Also, the symmetrical components for these voltages (zero, positive, and negative sequences) are $(\|V_0\|, \|V_1\|, \|V_2\|) = (1.94, 235.66, 0.70)$ V and $(\angle V_0, \angle V_1, \angle V_2) = (96.1°, -0.58°, 26.54°)$. For this case, the voltage unbalance is worked out about 0.297% according to both the IEEE standard 1159 and NEMA, corresponding to the load unbalance currents $(\|I_a\|, \|I_b\|, \|I_c\|) = (600, 500, 425)$ A. This figure can worsen during heavy load conditions. Thus, the need for compensation of the source current unbalance and consequently reduction of the load voltage unbalance is vital for supply quality improvement.

## 4. Equipment description

The Khoshnoodi D-STATCOM was installed across the low-voltage 400 V bus, as shown by Fig. 3. It is composed of two distinct elements, power circuit and control unit (see Figs. 1(a) and 2). We first review the necessary conditions for design of the power circuit, and then explain different parts of the control unit.

### 4.1. Power circuit

The power circuit consists of 400 V ac distribution substation, an equivalent commutation inductance, an ac/dc converter, and an equivalent dc capacitance. The bi-level converter uses two IGBTs for each leg. When a switch is OFF, then the capacitor dc voltage will drop across it. Considering the steady-state operation of D-STATCOM illustrated by Fig. 1(b), we assume the dc voltage $V_{dc}(\alpha)$ rises to $1.25V_{dc}$ ($i_q = 0$) in capacitive mode for negative $\alpha$, and will drop to $0.75V_{dc}$ ($i_q = 0$) in inductive mode for positive $\alpha$. Here, the blocking voltage of the switches is smaller than 780 V (1.25 times the dc voltage of uncontrolled full-bridge rectifying case) in the worst case. Thus, choosing an IGBT rated for 1200 V–400 A provides sufficient steady-state blocking voltage margin, more than 50%. Meanwhile, the installed D-STATCOM rated current is 360 A. Two shunted legs were designed for each phase, resulting in about 100% steady-state forward current margin. This will not only guarantee the reliable operation of the device but also provide the possibility for rating expansion.

#### 4.1.1. Commutation inductance

Let $A$ be defined as the gain of D-STATCOM, the ratio of the converter fundamental rms voltage ($|V_C|$) to the applied rms voltage ($|V_s|$). Hence, considering a fundamental 50 Hz voltage with a relative phase difference $\alpha$ between $V_C$ and $V_s$, using the fundamental power theory [6], both the produced reactive power $Q$ and the absorbed real power $P$ can be obtained and expressed by two functions of $\alpha$ and $L$ as follows:

$$\begin{cases} Q = \pm\dfrac{|V_s|^2}{\omega L}(A\ \cos(\alpha) - 1) \\ P = \pm\dfrac{|V_s|^2}{\omega L}A\ \sin(\alpha) \end{cases} \tag{2}$$

where $L$ is the commutation inductance. Also, $\alpha$ belongs typically to a small linear region as shown by Fig. 1(b) such that positive signs in (2) are used for $\alpha > 0$ ($A < 1$), and negative signs for $\alpha < 0$ ($A > 1$). Our experimental work on inverters shows that the optimized efficiency of D-STATCOM will be about 92% for designing a ±250 kVAr D-STATCOM. Also, the wider the chosen range for the gain $A$, the bigger the commutation inductance $L$ can be designed. Meanwhile, choosing high gains will raise the converter cost though. Hence, for a fixed modulation index (e.g. 0.9 to get high harmonic performance), the gain $A$ was chosen to vary in [0.75, 1.25] consistent with voltage rating of the selected switches. Here it is assumed that the power losses for supplying 250 kVAr (either capacitive or inductive) are equal to 20 kW (including the switching, snubbers, dc-side, and ac-side losses). Two equations in (2) can be worked out to assign an upper bound to the commutation inductance $L$:

$$L \leq L_{max} \approx -\frac{A_{max}|V_s|^2 \sin(\alpha_C)}{P\omega} \approx \frac{A_{min}|V_s|^2 \sin(\alpha_L)}{P\omega} = 510\ \mu H \tag{3}$$

where $A_{max} = 1.25$, $A_{min} = 0.75$, $|V_s| = 400$ V, and $\alpha_C = -0.912°$ and $\alpha_L = 1.53°$ are calculated using (2). It can be seen from (3) that $L_{max}$ varies when the gain $A$ belongs to a different range. Here we have chosen $L = 0.5$ mH to ensure that the rated reactive power is generated by D-STATCOM. In practice, $L$ is chosen to be close to its upper bound to limit a probable fault current down to its lowest possible value as well as improving harmonic performance.

#### 4.1.2. AC filter

Here a low-pass filter (LF) is designed to damp out high-frequency ripples of converter output waveforms. To model the Khoshnoodi substation, its local distribution network was studied, resulting in an independent source in series with an inductance $L_s = 147\ \mu$H. Fig. 5(a) shows that the converter is connected to this model through an ac passive filter.

First, the transfer function $Y(s) = i_C(s)/V_C(s)$ (the admittance seen from the converter) is approximated. To this extent, $Y(s)$ should be very close to zero at switching frequency $f_s = 2550$ Hz. Hence, two complex conjugate zeros are placed right after $f_s$, namely at $s = j2\pi \times 2600$ rad/s, to get more attenuation than a pure inductive filter. Now, the transfer function has two complex zeros, which needs two complex poles to suit its phase relationship. Hence, two complex poles are placed far enough from the zeros, while keeping enough distance from the 5100 Hz ripple to prevent a possible accentuation at this frequency. Hence, they are chosen to be equal to $s = \pm j2\pi \times 3400$ rad/s.

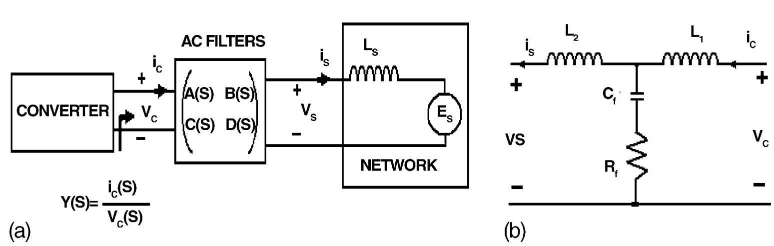


Fig. 5. (a) Equivalent circuit for the converter, ac filter, and the distribution network; (b) the resulting designed passive filter circuit.

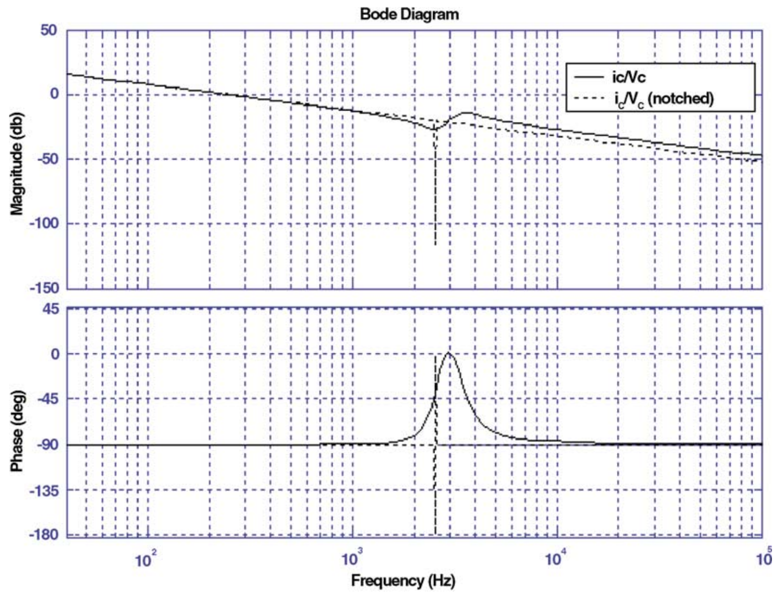


Fig. 6. Bode diagrams for the admittance seen from the converter output $\left(Y(\mathrm{j}\omega)=\frac{i_{\mathrm{C}}(\mathrm{j}\omega)}{V_{\mathrm{C}}(\mathrm{j}\omega)}\right)$ along with the notched frequency response of $\frac{i_{\mathrm{S}}(\mathrm{j}\omega)}{V_{\mathrm{C}}(\mathrm{j}\omega)}$.

Additionally, the LF transfer function needs a pole at origin (ignoring series resistances) to introduce inductive phase relationship. Particularly, this admittance needs to be equal to

$$Y(s=j100\pi)=\frac{1}{j100\pi(L+L_{\mathrm{s}})}=-j4.92,$$
$$\text{at}\quad f=50\,\mathrm{Hz}$$

where $L$ is the calculated commutation inductance of D-STATCOM. Applying these considerations will lead to the following approximate transfer function with two zeros and three poles:

$$Y(s)=\frac{2642.4(s^2+16328^2)}{s(s^2+21352^2)} \tag{4}$$

Second, the filter elements can be synthesized by finding its *ABCD* parameters from the approximated transfer function. Considering Fig. 5(a), the admittance seen from the converter is $Y(s)=\frac{C(s)L_{\mathrm{s}}(s)+D(s)}{A(s)L_{\mathrm{s}}s+B(s)}$, which in combination with other circuit rules will eventually result in the filter's ABCD parameters ($R_{\mathrm{f}}$ is excluded).

$$\begin{pmatrix} A(s) & B(s) \\ C(s) & D(s) \end{pmatrix} = \begin{pmatrix} 1+5.283\times10^{-9}s^2 & s(6.429\times10^{-13}s^2 \\ & +500.14\times10^{-6}) \\ 13.96\times10^{-6}s & 1+1.699\times10^{-9}s^2 \end{pmatrix} \tag{5}$$

where this transfer matrix can now be introduced by its three first-order factors

$$\begin{pmatrix} 1 & 378.4\times10^{-6}s \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 13.96\times10^{-6}s & 1 \end{pmatrix} \times\begin{pmatrix} 1 & 121.7\times10^{-6}s \\ 0 & 1 \end{pmatrix} \tag{6}$$

These three transfer matrices represent a LCL circuit with $L_1=378.4\,\mu\mathrm{H}$, $C_{\mathrm{f}}=13.96\,\mu\mathrm{F}$, and $L_2=121.7\,\mu\mathrm{H}$ as shown by Fig. 5(b). Inserting a $1\,\Omega$ resistor ($R_{\mathrm{f}}$) in series with the capacitance $C_{\mathrm{f}}$ will result in a much smoother response compared to that of the non-resistive circuit. The Bode diagrams ($|Y(j\omega)|$ and $\angle Y(j\omega)$) are illustrated by solid line curve in Fig. 6. Nevertheless, the dotted line curve demonstrates the frequency response of the filter output current $\frac{i_{\mathrm{s}}(j\omega)}{V_{\mathrm{C}}(j\omega)}$ when it is notched by a *LC* branch tuned at the carrier frequency of the PWM scheme.

#### 4.1.3. DC capacitor

An angle-controlled D-STATCOM, discussed earlier in Section 2, is controlled over a linear region. In [2], the characteristic equation of this linearized system is given by:

$$s^3+s^2\left\{\frac{2r_{\mathrm{s}}\omega_b}{L'}+\frac{\omega_b C'}{r_{\mathrm{p}}}\right\} +s\left\{\frac{r_{\mathrm{s}}\omega_b}{L'}\left(\frac{r_{\mathrm{s}}\omega_b}{L'}+\frac{2\omega_b C'}{r_{\mathrm{p}}}\right)+\omega_b^2+\frac{3k^2\omega_b^2C'}{2L'}\right\} +\left\{\frac{\omega_b^3C'}{r_{\mathrm{p}}}\left(1+\frac{r_{\mathrm{s}}^2}{L'^2}\right)+\frac{3k^2\omega_b^3C'r_{\mathrm{s}}}{2L'}\right\}=0 \tag{7}$$

where $\omega_b=100\pi$ rad/s is the system radian frequency, $r_{\mathrm{s}}$ the ac series resistance in p.u., $L'=\frac{L\omega_b}{z_b}$ in p.u., $r_{\mathrm{p}}$ the shunt dc resistance in p.u., $C'=\frac{1}{z_bC\omega_b}$ in p.u., $k=\frac{4}{\pi}$, and

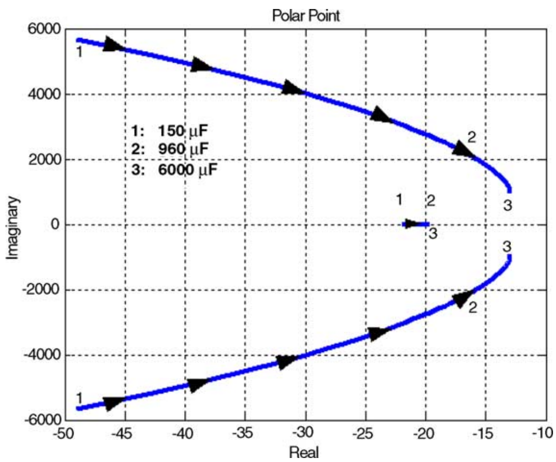


Fig. 7. A polar plot for three eigenvalues obtained from (7) by varying the capacitance $C$ within [150 μF, 6000 μF].

$z_b = 400/360\,\Omega$. Considering the base impedance $z_b$, these parameters are available for the designed D-STATCOM: $L' = 0.1442$ p.u., $r_s = 0.02$ p.u., $r_p = 90$ p.u. For a given $C'$, roots of (7) present the eigenvalues of the device. Two complex and one real eigenvalues indicate the dynamic response of D-STATCOM.

A polar plot of these eigenvalues is shown by Fig. 7 in which $C$ varies within [150 μF, 6000 μF] or $C' \in$ [19 p.u., 0.48 p.u.]. As seen from Fig. 7, the damping of the complex eigenvalues is reduced from −49 to −13, and the real one from −22 to −19. The bigger the capacitance $C$, the lower the damping and the slower the dynamic response of D-STATCOM. Nevertheless, even for a very big capacitance, the D-STATCOM is still a highly damped and stable system. Here the eigenvalues of D-STATCOM are independent of $\alpha$, i.e. independent of the control strategy applied.

However, the transfer function $\frac{\Delta i_q(s)}{\Delta\alpha(s)}$ has two complex zeros, which are dependent on $\alpha$. These zeros occur at lower frequency than the poles as long as $i_q$ is smaller than a critical reactive current. Beyond this critical current, the bode diagram shows a little phase margin near the system resonant frequency. A non-linear state variable feedback control is suggested in [2] to overcome this problem by causing improvement in the phase margin.

Further, it is shown in [2] that for a specified input voltage, as the capacitance $C$ increases, the fundamental negative sequence current decreases gradually down to zero at $C_c = \frac{k^2}{8L\omega_b^2}F$ and then rises up sharply to infinity at $C_i = \frac{k^2}{2L\omega_b^2}F$. Similarly, the third harmonic current first slowly rises and then asymptotically approaches to infinity at $C = C_i$. For the designed D-STATCOM, $C_c$ and $C_i$ are worked out as 3.9 mF and 15.6 mF, respectively.

Moreover, under transient conditions, this equipment needs to keep its dc-level for a few milliseconds. Assume D-STATCOM is operating in a steady state, $V_{dc0} = 500$ V, $P = 20$ kW, and $Q = 250$ kVAr. Also, let the equipment be subjected to a transient, which needs to supply the active power losses $P$ for quarter of a cycle. To achieve this, the energy stored in the capacitor must be at least 100 J. When the dc voltage is 500 V in an inductive mode, then $E = \frac{1}{2}CV_{dc0}^2$ gives the minimum capacitance as $C = 800$ μF. In practice, $C$ must be larger, because the dc voltage should be kept close to its nominal value to work properly. Let the voltage fall to 350 V at the end of transient. The capacitance must now be 1.57 mF. Note that with this capacitance, the dc voltage would fall from 750 V to 655 V in a capacitive operational mode. Taking the above discussed points into account, a capacitance bigger than 1.5 mF and smaller than 4 mF could be chosen for the dc-side.

### 4.2. Control unit

Here the control unit focuses on states of D-STATCOM over the linear region to set the required operating points (see Fig. 1(b)), where a PWM scheme is used to synthesize the converter voltage. Several stages could be found in the control unit as shown by Fig. 2, showing the relationship among different electronic hardware. The angle-controlled D-STATCOM device controls reactive power by controlling the phase difference $\alpha$ over a linear region. Here 24,480 samples per cycle are taken from the low-voltage side (400 V) of the substation and stored in an erasable programmable read only memory (EPROM). Thus, the spacing between successive pulses is 0.0147° or 0.88′ (min); the accuracy of the controlled angle $\alpha$ is 0.44′ or half of a sample pulse width in the worst case. The installed device operates at main frequency 50 Hz, with an operating control range of $\alpha \in [-0.912°, 1.53°]$. Hence, to control reactive power flow to 1% of rated power (here 2.5 kVAr), an accuracy of 0.73′ (min) is required, which can be achieved by the employed device.

Using the electronic circuit shown by Fig. 8, the frequency of the mains supply is determined with a phase locked loop, and multiplied by 24,480 within the PLL. This resultant frequency is then used as a clock for a counter showing the address of the reference EPROM. At the same time, any changes in the relative phase angle $\alpha$ is added instantly to this address, and the counter reset to the resulting address. Simultaneously, a parallel circuit integrates the changes in the relative phase angle and stores an instantaneous $\alpha$ as the initial value. Whenever a zero voltage detector detects the zero-crossing of the mains supply voltage, the counter is reset to this initial value to manage a fast and accurate phase correction. Therefore, the IGBT-based converter and modern control electronics give the D-STATCOM a dynamic performance capability far exceeding that of other reactive power compensators.

Another EPROM stores the triangular carrier with the same clock as the reference EPROM. Thus, the period of the carrier changes exactly in accordance to the variations of the detected frequency of mains supply. Hence, despite any frequency changes, the ratio of the reference period over the carrier period ($M$) remains constant. In a balanced three-phase system, there is an equal 120° phase difference between any two phases. However, the phasing of the high frequency

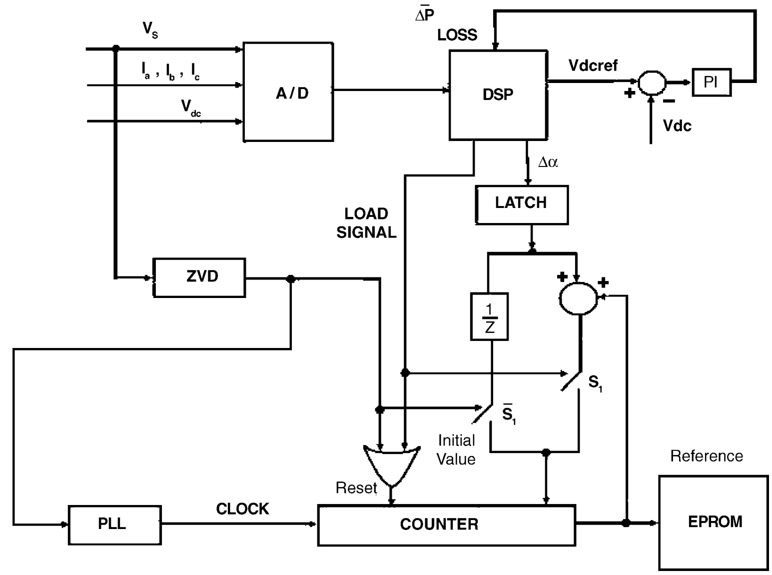


Fig. 8. The electronic circuit providing the relative phase angle $\alpha$ for the converter voltage.

carrier with respect to the mains supply frequency could be different for all three phases. To achieve an exact phase balance, the constant ratio $M$ could be considered as an odd multiple of three. Here $M = 51$ (480 samples per triangular waveform) was chosen for the device.

#### 4.2.1. *Voltage regulation and unbalance control*

The DSP analyzes the control algorithm for the unbalance issue along with either reactive power control or voltage regulation. It provides two reference signals, positive and negative sequence voltages ($V_C^+ \angle\alpha^+$ and $V_C^- \angle\alpha^-$),

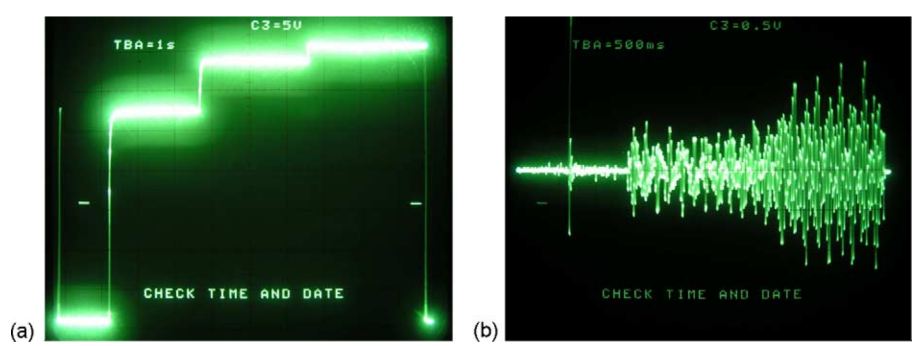


Fig. 9. Start-up sequencing: (a) dc voltage build-up during the three steps; (b) converter current during the start up.

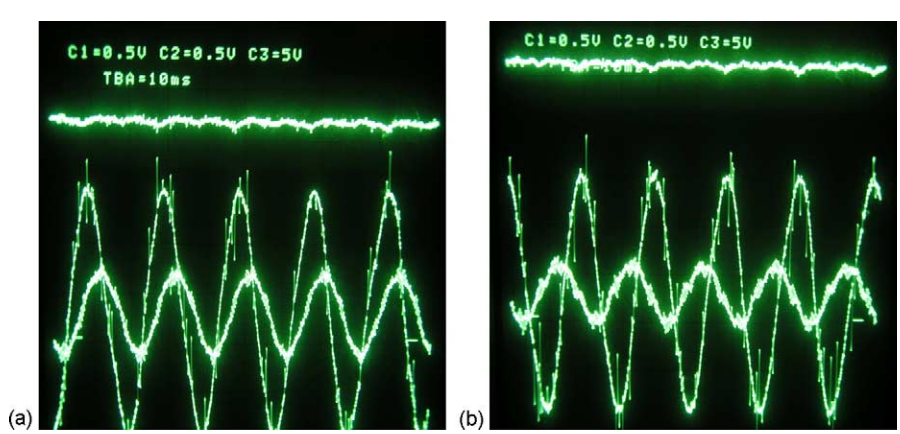


Fig. 10. Steady-state operation of D-STATCOM for (a) inductive mode and (b) capacitive mode.

that are added together to form the PWM reference $V_C\angle\alpha$ (see Fig. 8). Using a fundamental positive sequence detector (PSD), positive sequence voltage of ac network $\underline{V}_s^+$ is obtained. At the same time, the signal $\Delta\bar{P}_{loss}$ is provided by comparing the dc voltage $V_{dc}$ with the reference dc voltage $V_{dcref}$, and applying the difference to a PI controller. Also, the three-phase load voltages and currents are used to work out the needed reactive power [10]. Note that the DSP (TMS320VC5416) uses a Newton–Raphson algorithm to solve a set of equations to obtain the forgoing named positive and negative references. These equations are arranged based on imposing the required objectives to reduce the source-end current unbalance. A detailed description of this control algorithm could be found in [8].

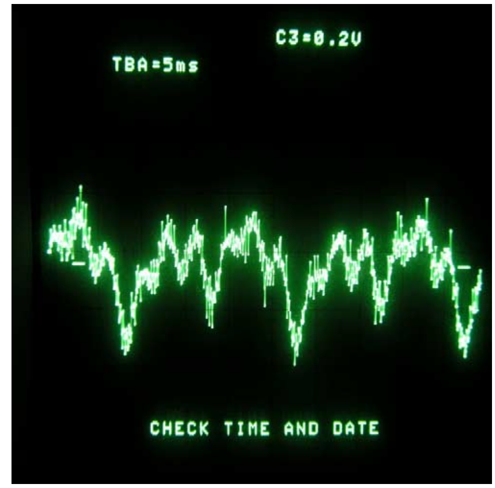


Fig. 11. dc-side voltage oscillations of D-STATCOM due to the grid unbalance.

## 5. Experimental results

Here various experimental results are presented including both uncontrolled and controlled tests. It should be explained that start up and shut down sequencing are managed by DSP through the CTRL board. Start up sequence of D-STATCOM is done in three steps. First, it is connected to the 400 V bus as a rectifying device to charge the dc capacitors close to their nominal voltage. A resistor limits the drawn current. Then, the converter's switches are pulsed to operate as a D-STATCOM, while the starting resistor still limits the converter current. Finally, a contactor will bypass this starting resistor for normal operation of D-STATCOM. The mentioned sequence was recorded and is depicted by Fig. 9(a and b) in which the three named steps are clearly shown. Fig. 9(a) gives the dc voltage built up, and Fig. 9(b) shows the D-STATCOM current. At the end of this process, the starting resistor is bypassed, and the phase angle $\alpha$ is available to be determined in a closed loop.

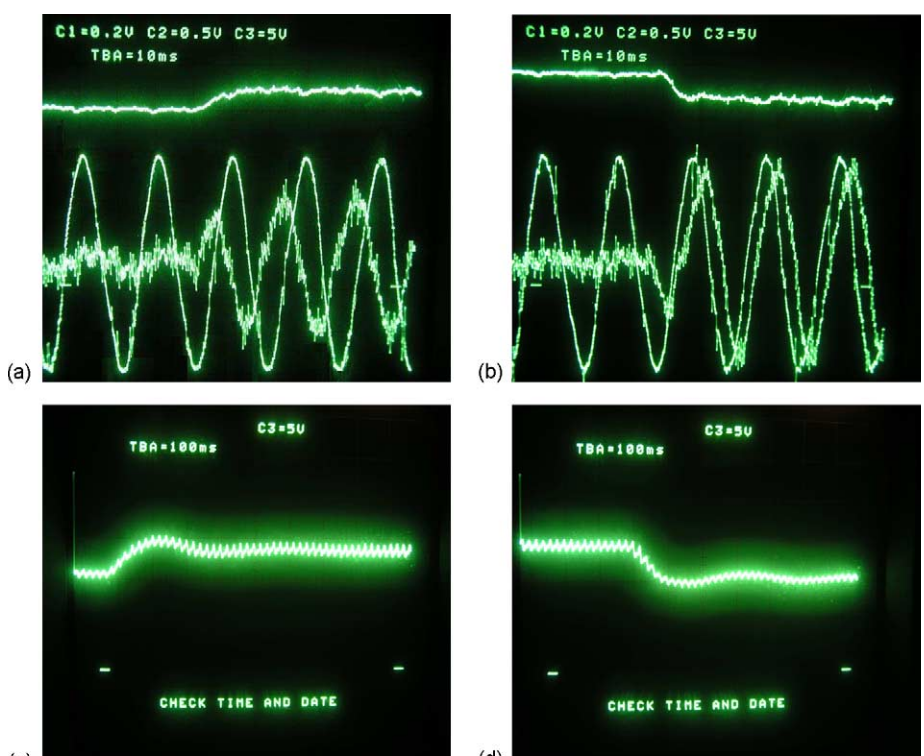


Fig. 12. Uncontrolled dynamic response of D-STATCOM for two cases: (a) transition from inductive to capacitive mode, and (b) transition from capacitive to inductive mode; (c and d) the dc voltage transition under a controlled program by the DSP.

### 5.1. Uncontrolled tests

Here the magnitude and angle of a positive sequence voltage are manually entered as the reference for the PWM scheme to be synthesized by the converter. First, under an uncontrolled situation, steady-state operation of D-STATCOM is considered for both inductive ($\alpha > 0$) and capacitive ($\alpha < 0$) VAr compensation. Fig. 10(a) shows an inductive mode, where the current lags the applied voltage. Fig. 10(b) depicts a capacitive mode, where the current leads the applied voltage by about 90°. Here the dc voltage in capacitive mode is bigger than that of inductive mode as it is expected (see Fig. 1(b)).

However, both pictures illustrate a dominant 100 Hz along with 50 Hz oscillations on top of the dc voltage. This basically reflects the impact of the substation unbalance voltages on the dc voltage of the converter [7,8]. The necessity of dealing with unbalance issue is shown by Fig. 11, which clearly zooms in the dc voltage oscillations.

Second, transient of D-STATCOM is considered, again an uncontrolled case. The IGBT-based converter and modern control electronics give the D-STATCOM a dynamic performance capability far exceeding that of other reactive power compensators. Fig. 12(a and b) shows the transient behavior of D-STATCOM for two cases. First, a transition was recorded from absorbing reactive power (inductive mode—$\alpha > 0$) to supply reactive power (capacitive mode—$\alpha < 0$), which takes about half a cycle for D-STATCOM to approach another steady state. Second, the reverse was experimentally done, where the operating condition of D-STATCOM was changed from a capacitive to an inductive mode. Again, both 50 Hz and 100 Hz oscillations can be seen on the dc voltage due to the unbalanced applied voltages.

### 5.2. Controlled tests

Additionally, using a PI controller, the dc voltage is controlled, while the reference voltage contains negative sequence component. Here the D-STATCOM absorbs the needed energy by changing relative phase angle $\alpha$. Fig. 12(c and d) introduces transitions of dc voltage for the controlled cases corresponding to those of Fig. 12(a and b). It can be seen from the controlled figures that the dc voltage only contains switching frequency ripples compared to those of uncontrolled cases.

## 6. Conclusion

A ±250 kVAr D-STATCOM was designed and installed for the Khoshnoodi substation in Tehran's electrical distribution system. This prototype installation is an important step towards not only demonstrating IGBT-based technology for the first time in Iran, but also proving the equipment viability in practical distribution applications. The design procedure is detailed in two parts, power circuit and control unit. This paper discusses different aspects on selection of the commutation inductance, ac filter, and dc capacitor for the power circuit, and various electronic control blocks for the control unit. Further, several experimental results demonstrate a satisfactory operation and good performance for the installed D-STATCOM.

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## References

[1] P. Rao, M.L. Crow, Z. Yang, Statcom control for power system voltage control application, IEEE Trans. Power Deliv. 15 (October (4)) (2000) 1311–1317.

[2] C. Schauder, H. Mehta, Vector analysis and control of advanced static var compensators, IEE Proc. C 14 (July (4)) (1993) 266–272.

[3] L. Gyugy, Dynamic compensation of ac transmission lines by solid-state synchronous voltage source, IEEE Trans. Power Deliv. 9 (June (2)) (1994) 904–911.

[4] A.-A. Edris, et al., Proposed terms and definitions for flexible ac transmission systems (FACTS), IEEE Trans. Power Deliv. 12 (October (4)) (1997) 1311–1317.

[5] Tehran Local Electric Company, Iranian Electrical Standard Rules, Ministry of Energy, 2002, pp. 35–39.

[6] T.J.E. Miller, Reactive Power Control in Electric Systems, Wiley, 1982, pp. 40–69 (Chapter 1.6).

[7] C. Hochgraf, H. Lasseter, Statcom controls for operation with unbalanced voltages, IEEE Trans. Power Deliv. 13 (April (2)) (1998) 266–272.

[8] M. Tavakoli Bina, M. Eskandari, Consequence of unbalance supplying condition on a distribution static compensator, in: IEEE Power Electronics Specialists (PESC'04), vol. 8, June 2004, pp. 3900–3904.

[9] P. Pillary, M. Manyage, Definitions of voltage unbalance, IEEE Power Eng. Rev. 5 (May 2001) 50–51.

[10] F.Z. Peng, J.S. Lai, Generalized instantaneous reactive power theory for three-phase power systems, IEEE Trans. Instrum. Meas. 45 (February (1)) (1996) 293–297.