Operation Assessment of an installed ±75 kVAr STATCOM

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Abstract—**A Static Compensator (STATCOM) is a FACTS controller, which can either absorb or deliver reactive power to power systems. A ±75 kVAr STATCOM was installed for a substation in Tehran distribution system. This work demonstrates operation of an installed STATCOM while the imbalance of the substation on the STATCOM behaviour is considered. Different practical results show the quick variations of the capacitor voltage. This is due to an energy oscillation at twice the synchronous frequency between the dc and ac sides. This oscillation also introduces low order harmonics to the inverter output voltages and currents, causing distortion of waveforms along with a poor performance for STATCOM.**

Keywords—**STATCOM, angle control, voltage unbalance, FACTS**

I. INTRODUCTION

THE use of FACTS controllers can overcome disadvantages of electromechanically controlled transmission systems. The STATCOM can be employed as a parallel device in ac power systems, generating balanced three-phase sinusoidal voltages at fundamental frequency. The amplitude and angle of these voltages should be rapidly controllable. Different voltage-sourced inverters topologies could be implemented using GTOs and IGBTs for high power utility applications such as voltage regulation. The analysis of STATCOM as a FACTS controller is presented in [1]–[3].

Static var compensators (SVC) were first developed in late 1960 for the purpose of compensating large fluctuating industrial loads. By the late 1970, the necessity of dynamic compensation for power systems became evident. Later on, using 2500 V – 2000 A GTOs, and then 4500 V – 3000 A and higher GTOs provided the possibility of generating or absorbing controllable reactive power by high rating modules.

Meanwhile, an IGBT is faster than a GTO, introducing lower dissipation power as well. The power levels of IGBTs are lower than GTOs though. Nevertheless, voltage levels for distribution systems are low. Hence, IGBT switches could be employed as an alternative to GTOs. This paper describes the application of new technologies to a ±75 kVAr prototype installation, and provide an outline of the development work associated with it.

A *STATCOM Operating Principles*

Fig. 1(a) shows a three-phase STATCOM, comprising a voltage-sourced inverter connected through an inductance in series with a transformer to a power system. The converter may consist of several six pulse voltage-sourced converters to improve the harmonic performance of STATCOM. The capacitor carries the dc voltage V_C. The contactor C1 connects the power electronic device to the power system. The contactor C2 in parallel with a current limiting resistor is used for starting process. During the normal operation of STATCOM both contactors are closed. Now suppose both the ac system voltage $\mathbf{v}$ and the converter-composed voltage $\mathbf{v}'$ are in phase. When $\mathbf{v}' > \mathbf{v}$, STATCOM delivers reactive power to the power system. When $\mathbf{v}' = \mathbf{v}$, reactive power is zero. When $\mathbf{v}' < \mathbf{v}$, STATCOM absorbs reactive power from the power system. Thus, by varying $\mathbf{v}'$, reactive power can be controlled to emulate a certain application such as voltage regulation.

However, for stable operation of STATCOM, the converter output has a small phase difference with the ac system voltage (α). In other words, the current flows through STATCOM contains both reactive and active components. In fact, changing α will vary the dc voltage V_C, and consequently the con-

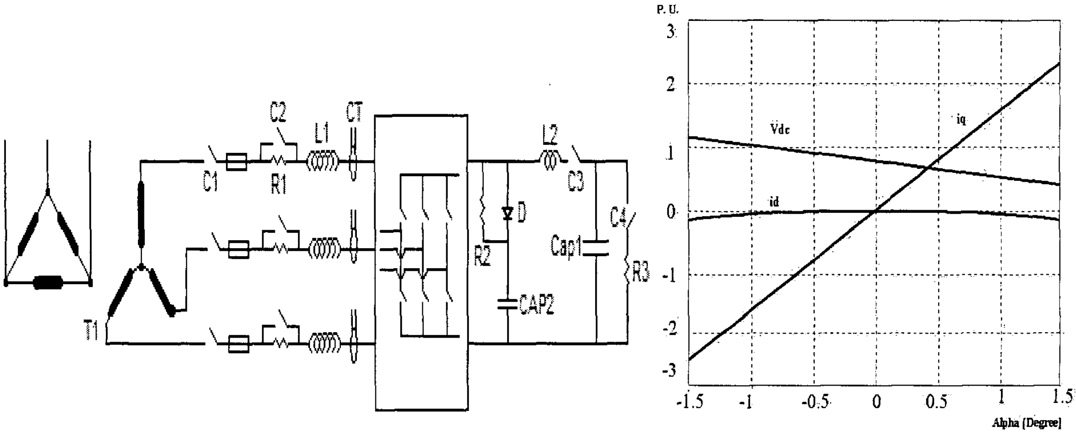

Figure 1: (a) Single-line diagram of the experimental of STATCOM; (b) equivalent reactive current, active current, and capacitor voltage as a function of α.

verter output $\mathbf{v}'$. 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 STATCOM.

A typical steady state operation of STATCOM as a function of α is depicted in Fig. 1(b). Three state variables $\mathbf{i}_d$, $\mathbf{i}_q$, and V_C give the equivalent active current, reactive current, and dc voltage respectively. This figure shows almost a linear relationship for the $\mathbf{i}_q$ as a function of α over $[-1.5°, 1.5°]$, although the state equations represent a nonlinear system. When α is negative, STATCOM works in capacitive mode, and positive α corresponds to inductive mode. This suggests a way of controlling STATCOM, mainly by α.

B. Application Background

The substation of Khoshnoodi is working as one of the principal nodes of Tehran distribution system. This node is connected to three other substations, acting as a central role in the network configuration. It serves a big area including eight feeders of both industrial and residential customers using a 20 kV/0.4 kV, 1.6 MVA transformer. The substation is able to communicate with Tehran dispatching center for its operation settings.

The 0.4 kV bus experiences variation of voltage during both light and peak load conditions. The control algorithm of the installed STATCOM is based on programmable digital signal processing (DSP). One of the objectives of the developed device is to regulate this voltage by either absorbing or injecting the needed reactive power. However, this paper provides experimental results showing the satisfactory operation of STATCOM as well as giving the imbalance effects of the applied voltages on the behaviour of STATCOM.

C. Equipment Description

The installed STATCOM is composed of two distinct elements, power circuit and control unit. A single line diagram of the Khoshnoodi prototype STATCOM with its overall control system is shown schematically in Fig. 1(a). The power circuit employs IGBTs rated for 1200 V and 200 A (air cooled using fan), the commutation inductance $L = 1$ mH, and the dc capacitor bank $C = 940\mu$F.

Several stages could be found in control circuit. Initially, the sampling circuits monitor the phase voltages of the distribution substation 400 V bus, the capacitor dc voltage, and the converter currents injected to the substation. Then, they are digitized using fast analogue to digital converters (about 1 MHz A/D) and conducted to a microprocessor. These samples together with the STATCOM currents are used for SPWM board to synchronize the generated

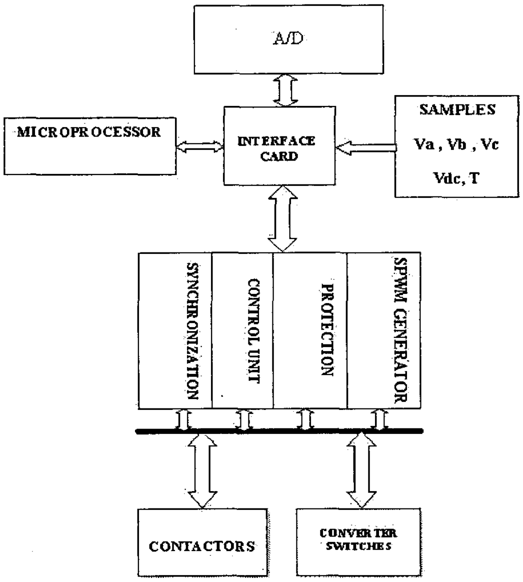

Figure 2: Schematic block diagram of digitized processing unit including main control, protection, and SPWM boards.

sine waveform with the applied voltage, measuring the frequency, producing the phase difference α, providing different protections, and managing main control unit of the converter. Fig. 2 illustrates a general description of the installed STATCOM.

Starting up the STATCOM is done in three steps. First, it is connected to the 400 V bus as a rectifying device to charge the dc voltage close to its nominal state. Then, the converter switches are pulsed as a STATCOM, while the starting resistor R_s limit the converter currents. Finally, a contactor will bypass starting resistor for normal operation of STATCOM.

D. Protection

Various single-phase and three-phase protections are designed for the system. These protective devices are responsible for preventing overcurrent, overvoltage, over-temperature of heat sinks, and undervoltage of power supply. Thus, as soon as a protective device detects a faulty condition, the gate pulses are abandoned and other necessary commands are issued for different parts of the circuit. Note that the temperature of converter heat sinks are also monitored using NTC resistors for over-temperature protection unit.

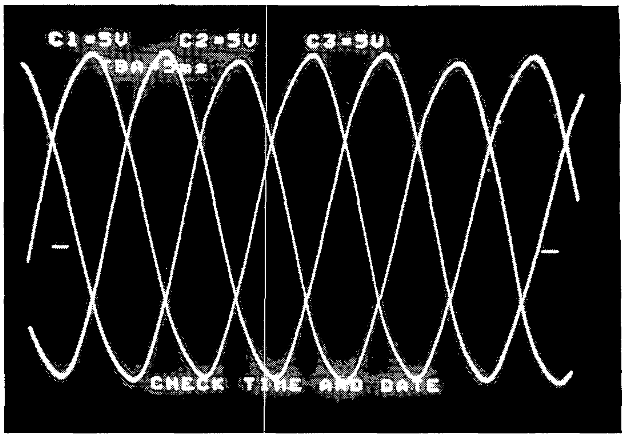

Figure 3: Three phase voltages of Khoshnoodi substation as the applied voltages to STATCOM.

II. EXPERIMENTAL RESULTS

Three phase voltages of Khoshnoodi substation are given in Fig. 3, showing an unbalance case (the harmonic contents are negligible). This study show the behaviour of STATCOM while a small imbalance are discussed. Magnitudes and angles of the applied voltages are accurately calculated by MATLAB, resulting in

$$\begin{cases} (||v_a||, ||v_b||, ||v_c||) = (236, 234, 237)V \\ (\angle v_a, \angle v_b, \angle v_c) = (0^\circ, -121^\circ, 119.45^\circ) \end{cases} \quad (1)$$

where applying the symmetrical components transformation to these phase voltages provide the positive, negative and zero sequence values as follows:

$$\begin{cases} (||V_0||, ||V_1||, ||V_2||) = (1.94, 235.66, 0.70)V \\ (\angle V_0, \angle V_1, \angle V_2) = (96.1^\circ, -0.58^\circ, 26.54^\circ) \end{cases} \quad (2)$$

Under this unbalanced situation, Fig. 4(a) shows an inductive mode, where α is positive. The current lags the applied voltage by about 90°, where the capacitor dc voltage oscillates at 100 Hz. Fig. 4(b),

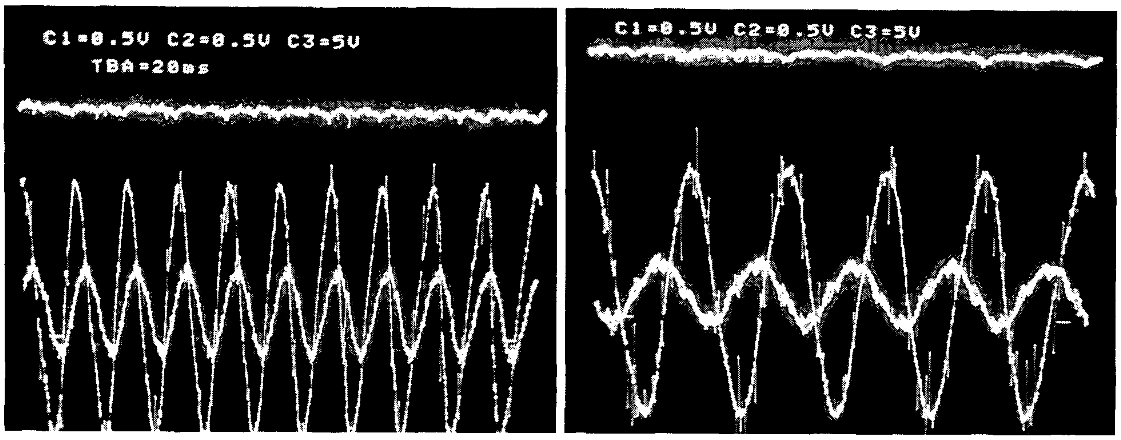

Figure 4: Two distinct experimental cases showing the applied voltage and STATCOM current for (a) a sample inductive mode ($\alpha > 0$); (b) a sample capacitive mode ($\alpha < 0$).

however, illustrates a capacitive mode, where α is negative. The dc voltage is bigger than that of inductive mode, again as it is expected.

Note that the voltage unbalance can be calculated 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 NEMA [7]. For the described case under study, the voltage unbalance is worked out about 0.5

Additionally, the transient behaviour of STATCOM are shown in Figs. 5(a)–(b) for two cases; First, STATCOM is absorbing reactive power (inductive mode – $\alpha > 0$) that suddenly the control angle α is changed to a negative value to supply reactive power (capacitive mode). It can be seen that the capacitor dc voltage rises from 360 V to 380 V as it is theoretically expected from Fig. 1(b).

Two points are considerable for the unbalanced situation. First, the capacitor dc voltage oscillates at twice the synchronous frequency. Second, the results show distorted waveforms due to the converter distorted output voltage. This also relates to the dc voltage oscillation. A control algorithm presented in [4]–[6] that could improve this problem by using the phase voltages ratios to build up an inactive compensation current.

Starting process of STATCOM is depicted by Fig. 6(a)–(b), where three steps are clearly shown. The left figure gives the dc voltage built up, where the right one provide the STATCOM current. At the end of starting process the starting resistor R_s will be bypassed, and the control angle α is available to be adjusted.

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III. CONCLUSION

The application of a ±75 kVAr STATCOM is studied using the conventional control of phase angle α. The experimental results show satisfactory operation and good performance for STATCOM. A small imbalance in Khoshnoodi substation demonstrate the distortion of waveforms because of presence of negative sequence components. The capacitor voltage oscillates at twice synchronous frequency, imposing low order harmonics (mainly the third and the fifth current harmonics) to the inverter currents. Consequently, STATCOM harmonic performance under this condition is not as good as its balanced operation. To remedy this problem, the

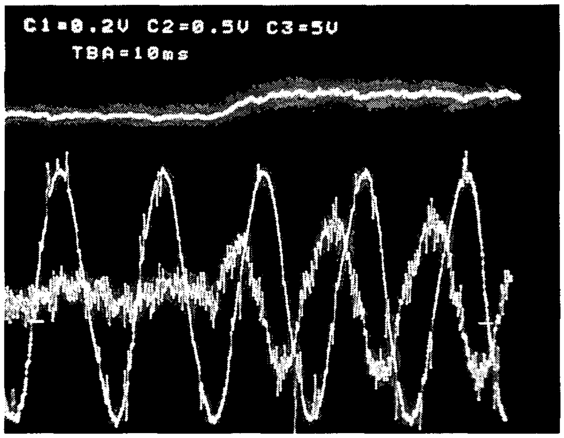

Figure 5: The flexibility of STATCOM when changing from inductive to capacitive mode.

control samples should be modified to improve the stated matters.

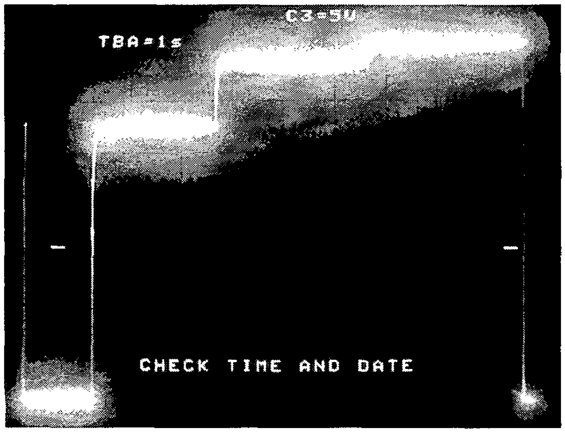

Figure 6: Start-up process in three steps, dc voltage build-up during these steps are shown.

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