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Design and experimental analysis of an advanced static VAR compensator with computer aided control

Erdal Irmak [a,*], Ramazan Bayındır [a], Ali Köse [b]

[a] Gazi University, Faculty of Technology, Electrical and Electronics Engineering Department, Ankara, Turkey
[b] Gazi University, Technical Sciences Vocational Colleague, Ankara, Turkey

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ABSTRACT

This study presents integration of a real-time energy monitoring and control system with an advanced reactive power compensation unit based on fixed capacitor-thyristor controlled reactor (FC-TCR). Firing angles of the thyristors located in the FC-TCR are controlled by a microcontroller in order to keep the power factor within the limits. Electrical parameters of the system are measured by specially designed circuits and simultaneously transferred to the computer via a data acquisition board. Thus, real time data of the system can be observed through a visual user interface. The data obtained is not only analyzed for control process, but also regularly saved into a database. The system has been tested in laboratory conditions under different load characteristics and experimental results verified that the system successfully and accurately achieves compensation process against the all operational conditions.

1. Introduction

The energy quality is an important issue nowadays and it depends on continuity of energy, fixed grid frequency, constant and sinusoidal supply voltage, value of the power factor, balance of phase voltages and currents, and the harmonic distortions [1–3]. Among these criteria, power quality is of great importance and can be improved with compensation of reactive power. Due to usage of loads with low power factors in industry and the increase of nonlinear devices in power systems, energy generation and distribution companies have to produce additional reactive energy and to transfer it over transmission lines with high losses. Therefore, improving the power factor is a mandatory operation for all industrial enterprises in order to minimize the costs, and to provide the energy efficiency.

Reactive power compensation is defined as the management of reactive power to improve the performance of alternating-current (AC) power systems. In general, the problem of reactive power compensation is related to load and voltage support. In load support, the objectives are to increase the value of the system power factor, to balance the real power drawn from the AC supply, to enhance voltage regulation, and to eliminate current harmonic components. Voltage support is generally required to reduce voltage fluctuation at a given terminal of a transmission line. Reactive power compensation in transmission systems also improves the stability of the AC system by increasing the maximum active power that can be transmitted [4]. The reactive power drawn by non-compensated loads causes the voltage changes in a finite non-zero impedance grid. Operating the compensation structures on the load side is a practical solution way to reduce these changes [5–7].

Traditionally, the power factor correction process has been typically achieved by capacitor banks, synchronous motors, microcontroller based reactive power relays [5–9]. However, these conventional methods are usually inadequate for the loads that have high power and short transition times between turn-on and turn-off operations. For this reason, static VAR compensators (SVC) have been developed. SVCs adjust the susceptance in each phase by controlling the firing angles of the thyristor controlled reactor [10]. The SVC can be found in applications such as power line compensation, compensation of railway feeding system, reducing disturbance from rolling mills and arc furnace compensation [11].

Energy monitoring is another crucial subject for power systems. In the recent literature, different methods and various interface options are recommended for monitoring of energy consumed in industrial enterprises, buildings, schools and shopping centers [12–19]. Among several methods, computer based measuring and monitoring systems have been gained popularity [20–22]. A common solution in energy tracking and monitoring systems is to employ an energy analyzer. Measured electrical parameters can be seen on the analyzer screen or can be

* Corresponding author. Tel.: +90 312 202 85 52.
E-mail addresses: erdal@gazi.edu.tr (E. Irmak), bayindir@gazi.edu.tr (R. Bayındır), alikose@gazi.edu.tr (A. Köse).

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monitored from a computer using the communication port of analyzer. Moreover, the measured results are likely to be observed over the internet using GPRS, Modbus and TCP/IP protocols by using new generation energy analyzers. However, achieving the energy monitoring and power factor correction processes through a data acquisition (DAQ) board has not been sufficiently studied yet.

In this context, commercial ready-to-use energy analyzers has been not used in this study as a difference from similar ones in the recent literature. For this aim, special circuits have been designed which measure the required signals quickly. Thus, cost of the system is considerably reduced. Furthermore, the switching devices are triggered accurately without any delay in each alternance because of using dsPIC microcontroller which is capable of operating higher frequencies than similar microcontrollers. Thus, speed and accuracy of the system has been increased. Moreover, electrical parameters of the power system are measured continuously and transferred to the computer in real time via a Data Acquisition (DAQ) board. Accordingly, it is possible to monitor all system data in real time through a visual interface. The system designed has been tested under different types of loads and experimental results show that it has considerably quite response time and high accuracy as well.

2. Theoretical background of FC-TCR

Thyristor controlled SVC systems are combination of a thyristor controlled reactor with a fixed capacitor bank and can be classified as following [6,23,24]:

- Thyristor switched capacitor (TSC).
- Thyristor switched reactor (TSR).
- Thyristor switched capacitor-Thyristor controlled reactor (TSC-TCR).
- Fixed capacitor-Thyristor controlled reactor (FC-TCR).

Among these methods, this study focuses on the last one called as FC-TCR. The equivalent circuit of a FC-TCR is shown in Fig. 1(a). As seen on figure, the capacitor draws a constant current from the source (V_S). The reactive current (I_S) drawn from the source is controlled by adjusting the firing angles of thyristors (T_1 and T_2) which are connected in series to the reactor (L). FC-TCR can provide continuous lagging and leading VARs to the system. Leading VAR is supplied by the capacitor. For supplying lagging VAR, TCR is generally rated larger than the capacitor. While fixed capacitor produces reactive power, thyristor controlled reactor consumes it. The control characteristics of SVC is shown in Fig. 1(b) where ADB line points out the control range.

The SVC control range is described by

$$V_s = V_{ref} + X_s . I_s \tag{1}$$

where X_s is the inclination of the control characteristic line [27]. V_{ref} is the SVC voltage when $I_S = 0$.

The first step of SVC design process is the determination of the capacitor value. For this aim, the capacitive reactive power demand required for minimizing the voltage is calculated assuming the system operates as uncompensated. The result obtained determines the maximum capacitive power of SVC. Then, inductive reactance of TCR is determined depending on the rate of inductive and capacitive operating range. Using Kirchhoff equations, the value of the fixed capacitor and the value of the reactor are calculated with Eqs. (2) and (3):

$$V_s = \frac{(I.\ \sin\ \varphi)\max}{\omega.C} \tag{2}$$

$$V_s = \left[(I.\ \sin\ \varphi)\max - (I.\ \sin\ \varphi)\min\right].\omega.L \tag{3}$$

where V_s refers to the voltage applied, C refers to the capacity, L refers to the inductance, I refers to the circuit current, ω refers to the angular frequency of voltage. $(I.\sin\phi)_{\max}$ and $(I.\sin\phi)_{\min}$ indicate the maximum and the minimum values of lagging reactive currents, respectively. The current in TCR can be controlled by adjusting the firing angle (α) and its instantaneous value over half a cycle (i_{TCR}) is given by Eq. (4) [25]:

$$i_{\mathrm{TCR}} \left\{ \begin{array}{ll} = \frac{\sqrt{2}.V_s}{\omega.L}(\cos\ \alpha - \ \cos\ \omega t), & \alpha < \omega t < \alpha + \sigma \\ = 0, & \alpha + \sigma < \omega t < \alpha + \pi \end{array} \right\} \tag{4}$$

Similarly, the reactive power in the TCR is calculated by using Eq. (5) [26]:

$$\theta_{\mathrm{TCR}} = \frac{V_s^2}{\pi.\omega.L}(2\pi - 2\alpha + \ \sin\ 2\alpha) \tag{5}$$

The current waveform of a one-phase TCR is shown in Fig. 1(c). As seen, the current is non-sinusoidal and contains harmonics which are functions of the conduction angle (σ). The fundamental component of the TCR current (I_1) is given by [25]:

$$I_1 = B_{\mathrm{TCR}}(\sigma).V \tag{6}$$

$$B_{\mathrm{TCR}} = \frac{\sigma - \ \sin\ \sigma}{\pi.\omega.L} \tag{7}$$

The conduction angle σ is related to α as seen in Eq. (8).

$$\sigma = 2(\pi - \alpha) \tag{8}$$

All the equations and descriptions given above show that the power factor can be corrected continuously by adjusting the reactor current with the help of controlling thyristors. Thanks to using this method, compensators provide rapid response to the need of reactive power but produce discontinuous current waves and single-level discrete harmonic currents as a result of firing

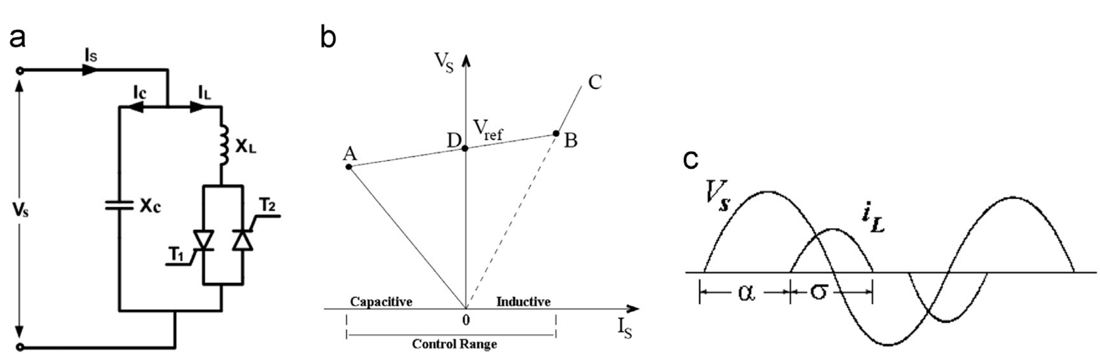

Fig. 1. (a) Simple power system model of FC-TCR. (b) Control characteristics of SVC. (c) Waveforms of V_S and I_L.

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