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Experimental studies of a scaled-down TSR-based SVC and TCR-based SVC prototype for voltage regulation and compensation

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Abstract

In this paper, prototypes of two shunt flexible AC transmission system (FACTS) devices, a thyristor switched reactor (TSR)-based static VAr compensator (SVC) and a thyristor controlled reactor (TCR)-based static VAr compensator- have been developed. The design and testing of both a TSR-based SVC and a TCR-based SVC are accomplished in the Power Systems Research Laboratory of Nigde University. The TSR-based SVC and TCR-based SVC devices are studied in three-bus and single machine infinite bus systems for three-phase static load conditions. The effects of TSR-based SVC and TCR-based SVC devices on load voltages are also analyzed. Experimental results show that significant improvement in reactive power compensation and voltage regulation is achieved by using TSR-based SVC and TCR-based SVC.

Key Words: *Flexible AC Transmission Systems (FACTS), Thyristor Switched Reactor-Based Static VAr Compensator, Thyristor Controlled Reactor, Voltage Regulation, Compensation.*

1. Introduction

Recently, voltage stability and voltage regulation have received widespread attention because power systems are interconnected to supply loads of large and distant regions [1, 2]. Different types of flexible AC transmission system (FACTS) controllers in AC systems can be used for compensation, voltage control, voltage regulation, voltage stability, controlling the phase angle, varying the line impedance, reactive power control, steady state stability, damping system oscillations, and controlling power flow in the transmission line [3-9].

The thyristor switched reactor-based static var compensator (TSR-based SVC) and thyristor controlled reactor-based static var compensator (TCR-based SVC) are two of shunt FACTS devices that have been used as an alternative to fixed shunt capacitors (FC) and fixed reactors (FR) in power systems. The shunt connected

SVCs, which are both reactive power generator and reactive power absorbers, are used for voltage regulation and compensation. The basic structure of a SVC consists of a fixed shunt capacitor and a thyristor controlled reactor [5, 6]. Furthermore, the SVC has been investigated in TSC-TCR, Mechanically Switched Capacitor (MSC)-TCR, and TSC-TSR configurations [6-16]. In this paper, the SVC structure contains a fixed shunt capacitor and a thyristor switched reactor. Moreover, the basic SVC (TCR-FC) structure is also considered in this study. A TSR-based SVC system does not inject harmonic components of voltages and harmonic components of currents into the line. Hence, a harmonic filter is not required for the testing the system with TSR-based SVCs, one of the great advantages of the device.

The Single Machine Infinite Bus (SMIB) system, in which a large system is reduced to an infinite bus with constant frequency, is often defined for industrial plants or distribution systems that are connected to huge transmission systems [14, 15]. The SMIB systems with FACTS devices such as SVC, UPFC, TCSC, STATCOM, and SSSC have been generally investigated for transient stability, fault analyses and damping oscillations in power systems [16-26]. However, usually theoretical studies and simulations of SMIB systems with FACTS devices were examined in these studies. A SVC prototype installed in a SMIB system has not been previously studied by research groups. In this paper, the developed TCR-based SVC prototype is used as a compensator and installed in a SMIB system.

In this work, we practically designed and studied TSR-based SVC and TCR-based SVC. Few works have presented a prototype of TSR-based SVC and TCR-based SVC for laboratory experiments or real-world applications [9-13, 27, 28]. Endres et al. [9] presented the design and operational testing of valves for SVC, which consist of one TSR and two TSCs. They installed the SVC at the Kemps Creek substation in Australia. Zemerick et al. [10] developed a microprocessor controlled personal SVC. They designed a var controller for displacement power factor correction of reactive loads. A 6-35 kV TSC device was developed and installed at substations in Beijing [11]. Here, microprocessor-based control was used and the detected voltage and current variations that occurred when the capacitors were switched on was examined. A microprocessor-controlled technique for constructing a GTO-based reactive power compensators was proposed and applied to a single-phase thyristor converter [12]. Stepless control of reactive power was obtained to achieve very fast response, but the control structure of the system was more complex and expensive for GTO-based compensators. Moreover, the generation of harmonics by switching capacitors at higher frequencies were aimed at being prevented. A TSC of 40 kVA, controlled by a microcontroller, was designed for 415 V for reactive power support [13]. The synchronous integration method was used for minimizing harmonics on the bus voltage. A PI controlled single-phase SVC was proposed to regulate the output voltage of the self-excited induction generator by Ahmed et al. [27]. The proposed device consists of a FC, a TCR and a TSC. The effect of the impedance of the single-phase SVC on harmonic magnification and voltage distortion was experimentally studied by Abdulla and Salameh [28].

In this paper, prototypes of TSR-based SVC and TCR-based SVC have been examined in the Power Systems Research Laboratory at Nigde University. The TSR-based SVC and TCR-based SVC devices are studied for three-bus, SMIB, three phase and static load conditions. Experimental studies have been conducted for uncompensated and compensated systems, and we have obtained graphs for output signals as a function of load voltage, power factor and voltage total harmonic distortion (THD_V) by an energy analyzer. The experiment results show that TSR-based SVC and TCR-based SVC located at the load bus provide reactive power and voltage regulation for static loads..

The paper is organized as follows: Section II briefly presents theory about TSR-based SVC and TCR-based SVC. The experimental studies of TSR-based SVC and TCR-based SVC are given in Section III. Finally, Section IV presents the conclusions of this study.

2. Theory of TSR-based SVC and TCR-based SVC

The most general structure of a static var compensator consists of a fixed shunt capacitor and a thyristor controlled reactor. A SVC is basically a shunt connected static var generator/customer whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables [5, 6, 29, 30].

In this paper, the TCR-based SVC prototype consists of one TCR, which contains two thyristors in anti-parallel and a reactor to be controlled, and one fixed capacitor (FC). Filters are traditionally used to absorb the harmonics generated by the SVC structure and large industrial loads. A three-phase SVC is comprised of three single-phase SVC's connected in a delta configuration. The delta connection of the SVC's prevents harmonics from passing through the transmission lines [5, 6].

Furthermore, to prevent the generation of harmonics, a TSR was employed instead of a TCR [7, 9]. TSRs are shunt compensators that can absorb reactive power [6] and have the properties of delaying one half cycle with no generation of harmonics [5, 6]. Figure 1 demonstrates an equivalent circuit of the TSR-based SVC. According to Figure 1, the TSR-based SVC consists of one TSR, which contains two thyristors in anti-parallel and a reactor to be switched, and one fixed capacitor (FC). In three-phase applications, the basic TSR-based SVC elements are connected in a delta configuration [5, 6].

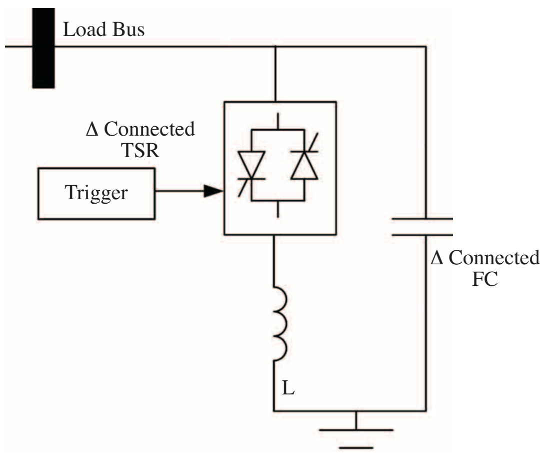

Figure 1. TSR-based SVC configuration.

The SVC has reactive and capacitive operation intervals. In this paper, the thyristors in the structure of the TSR are fired at the positive/negative peak of the source voltage or at the zero crossing of the line current, thereby preventing harmonic generation in power systems. Table 1 shows the performance comparison of TSR and TCR.

Table 1. The performance comparison of TSR and TCR.

The Compensator	Positive Characteristics	Negative Characteristics
TSR	No harmonic generation, Fast recovery time, Switched structure, Simple operating principle, In the 3-phase applications, it is connected in delta. It is used for compensation, regulation and damping of oscillations in power systems.	It is not able to prevent overvoltage. It can be in interaction with system at low frequencies. Its performance is variable.
TCR	Fast response time, Controlled structure, The control range is wide, In the 3-phase applications, it is connected in delta. It is used for compensation, regulation and damping of oscillations in power systems.	It generates harmonics. Its performance is variable. Operating principle is not simple.

3. Experimental studies

In order to evaluate operations of both TSR-based SVC and TCR-based SVC, we present two experimental studies of SVCs at the laboratory. The experiments include the following case studies: a) a three-bus system with TSR-based SVC, and b) a single machine infinite bus system with TCR-based SVC. In all experimental studies, systems with SVC and without SVC have been investigated, respectively. Additionally, in the second experiment, systems with and without generators have been examined.

High voltage components have been scaled-down for security reasons in the research laboratory. A real overhead power transmission line (360 km length, voltage of 380 kV and current of 1000 A) is represented by a 380 V line in the laboratory. A three-phase overhead power transmission line is modeled with a π equivalent circuit. In these experiments, all voltages and currents have been scaled-down by a 1:1000 ratio. Therefore, the voltage and current values measured in the experiments are converted to the 380 kV-level by a multiplication factor of 1000. The three-phase power supply unit has been utilized as an infinite bus. A three-phase synchronous generator of 1.1 kW has been employed as a generator. A six-pulse control unit is used to control the firing angles of thyristors in the TSR structure for three-phase applications. An energy analyzer has been employed to measure the voltage, power factor and voltage total harmonic distortion (THD_V) during these experiments. The load is selected as a static load, which is an ohmic-inductive structure. In this section, we present two experiment studies of SVC. Detailed descriptions of the example applications are given next.

3.1. A three-bus system with TSR-based SVC

In this study, an application of a three-bus system with TSR-based SVC is presented to show the effect of TSR-based SVC on voltage regulation. A one-line diagram of the studied system is given in Figure 2. In this study, the three-bus system consists of 120 km, 360 km and 360 km length transmission lines, which are modeled as a π-equivalent circuit. The 120 km transmission line has a line resistance of 4.3 Ω and a line inductance of 100 mH. The static load absorbs active power of 540 W and reactive power of 145 Var and two sources of 380 V have been used in this system. The three-phase TSR-based SVC prototype consists of three single phase

TSR-based SVC's connected in a delta configuration and connected in parallel to the load bus. A six-pulse generator is used to control the firing angles of the TSR for three-phase applications. Table 2 shows parameters of the transmission line and the source for this system.

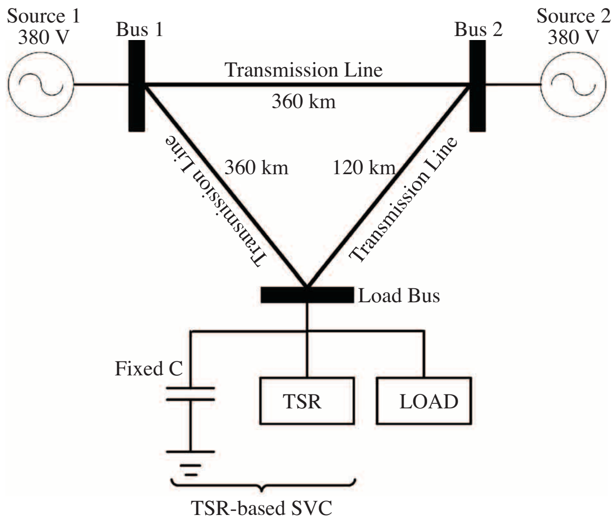

Figure 2. One-line diagram of the three-bus system with TSR-based SVC.

Table 2. The system parameters.

Source voltage	380 V
Network frequency	50 Hz
Line 1,2 R	6.5 Ω
Line 1,2 L	145 mH
Line 1,2 C	1 μF
Line model	π equivalent circuit
Line 1 and Line 2 length	360 km
Line 3 length	120 km
Line 3 R	4.3 Ω
Line 3 L	100 mH

First, the uncompensated system is considered. Figure 3 shows the practical system in the laboratory environment. As labeled in Figure 3, the devices used in the experiment are an AC power supply (#1) , a PC (#2), a breaker (#3), transmission line 1 (#4), transmission line 2 (#5), transmission line 3 (#6), a six-pulse generator and thyristors (#7), a TSR-based SVC (#8), an ohmic-inductive load (#9), a 0-30 V DC power supply for obtaining the firing pulse (#10), and an energy analyzer (#11).

Here, the effect of TSR-based SVC will be examined for reactive power compensation. Figure 4 shows variations of three-phase load voltages in a test period of 2 minutes for the 3-bus system. For the first minute, the uncompensated system is considered and the measured load voltage of 373 V is less than the nominal voltage for the static load. After this period, the TSR-based SVC prototype is installed in the system and the load voltage of 378 V is recorded for one minute. The load voltage becomes very close to the nominal value after installing the TSR-based SVC prototype. The inductive power of TSR-based SVC is 309 Var and its capacitive power is 408 Var.

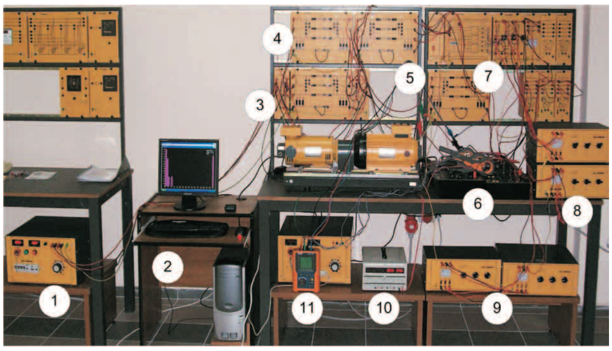

Figure 3. The practical system with TSR-based SVC.

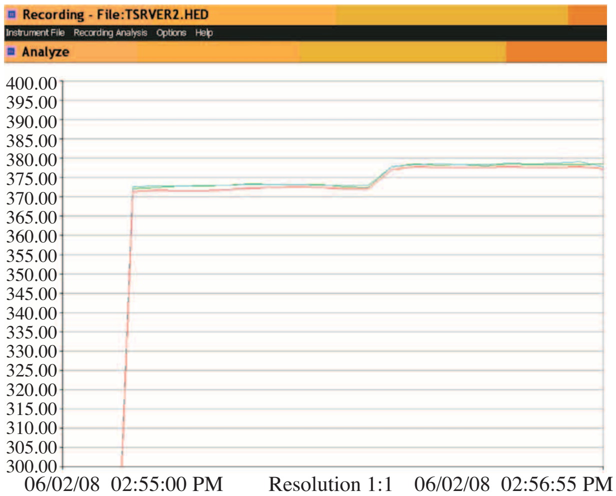

Figure 4. Load voltages in the three-bus system with a TSR-based SVC.

The waveforms of voltage total harmonic distortion (THD_V) are also investigated in this experiment. The waveforms of THD_V of the phase R (called U1 by the energy analyzer) for the uncompensated and compensated system can be seen from Figure 5 and Figure 6, respectively. For the first minute of the test period, a THD_V level of 8.42% for the uncompensated system is obtained, as clearly illustrated in Figure 5. As shown in Figure 6, the THD_V level for the system with a TSR-based SVC is 7.88%. These results show that the TSR-based SVC effects both voltage regulation and harmonic distortions. A system with TSR-based SVC does not need a harmonic filter, one of the great advantages of TSR-based SVC.

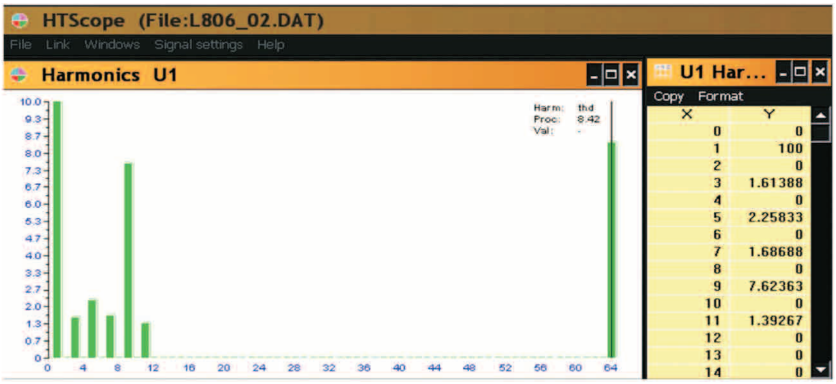

Figure 5. Voltage THD levels for the uncompensated system.

Lastly, Figure 7 illustrates the power factor (Cos ϕ) for the three-bus system with a static load after an experiment period of 2 minutes. As seen in Figure 7, the power factor of 0.96 lagging is acquired for the system without TSR-based SVC. In the system with TSR-based SVC, the power factor value is obtained as 1. Thus, the reactive power compensation is perfectly made using the TSR-based SVC.

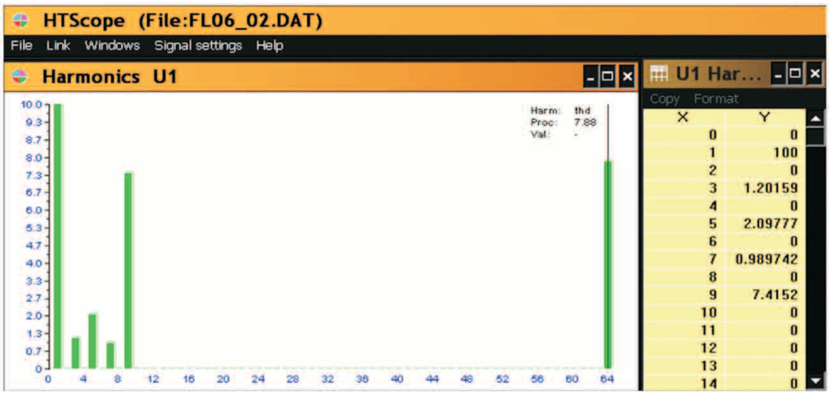

Figure 6. Voltage THD levels for the compensated system.

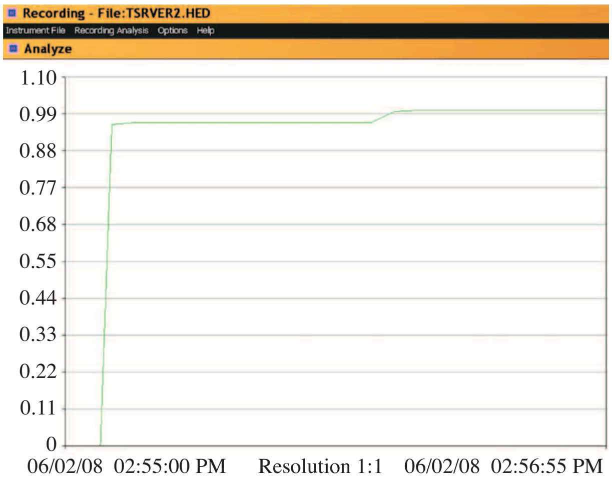

Figure 7. Power factor graphic for the system with TSR-based SVC.

3.2. A Single Machine Infinite Bus system (SMIB) with TCR-based SVC

In this case study, a Single Machine Infinite Bus (SMIB) system with TCR-based SVC is used to show the effect of TCR-based SVC on voltage regulation. Figure 8 demonstrates the SMIB system with the TCR-based SVC. For the SMIB system with TCR-based SVC, the practical system in the laboratory environment has the same structure as shown in Figure 3. In this case study, the system consists of two 360 km length transmission lines, which are modeled as a π-equivalent circuit. The 360 km transmission line has a line resistance of 13 Ω, a series inductive reactance of 290 mH, and a shunt admittance of 0.5 μF. The midpoint of the transmission line is selected as the load bus and the static load is chosen as a load. The load and TCR-based SVC are connected parallel to each other by a breaker in the middle of the long transmission line. The generator voltage is 380 V, the static load absorbs active power of 207 W and reactive power of 277 Var, and the total length of transmission line is 720 km. The voltage, frequency and characteristic of the infinite bus are constant for any load variation. Its parameters are a voltage of 380 V and a frequency of 50 Hz.

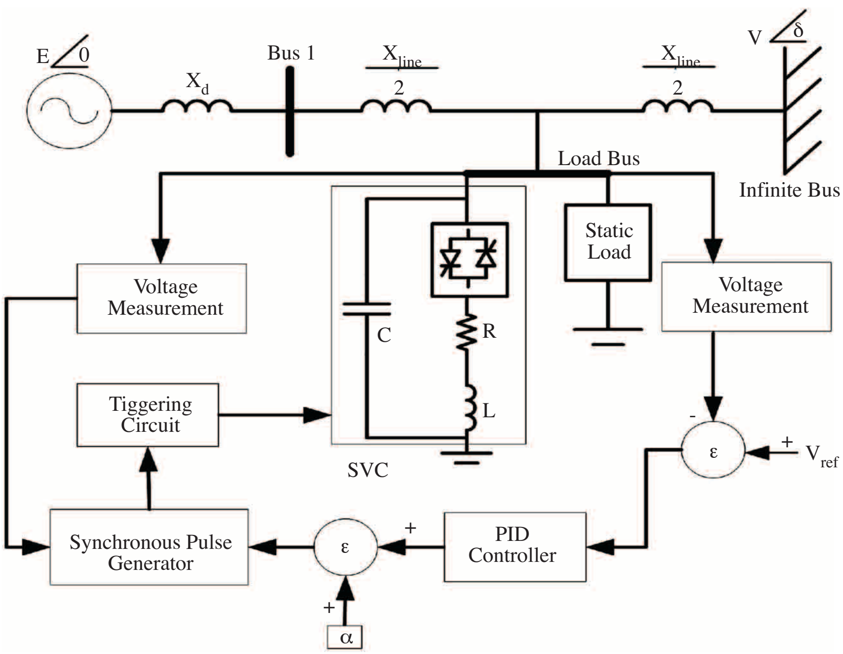

Figure 8. One-line diagram of the system with the SMIB.

A PID controller is used to control the firing angles of the TCR in the SVC structure. The load bus voltage, which is converted from AC to DC voltage by a rectifier circuit, is compared with the reference voltage. Their difference is used as the input to the PID controller. When the input voltage of this circuit is 220 V_{AC}, output voltage becomes 8.92 V_{DC}. Then, the reference voltage is adjusted to 8.92 V_{DC} value by a reference voltage generator module. The control output voltage is generated by the PID controller at a range of 0-10 V_{DC}. The output of the PID controller is applied to a trigger point limiter module as an input signal. The minimum angle level and maximum angle level are adjusted to 120° and 180° respectively by the trigger point limiter module. The SVC must be triggered in the capacitive region, because the experimental system being studied has ohmic-inductive loads. A six-pulse generator produces firing angles of thyristors according to the 0-10 V_{DC} voltage values on its input. The coefficients of PID controller are Kp=4, Ki=100 and Kd=0.8.

Figure 9 shows the variation in the load voltages for a test period of around 3 minutes for the SMIB system, both with TCR-based SVC and without TCR-based SVC. In the first 45 seconds, the uncompensated system is considered and the load is only fed by the infinite bus. The load voltage is measured as 330 V. After that, the generator is connected to the system and the load voltage increases approximately from 330 V to 348 V at the middle of the transmission line. The phase-phase voltage of the generator has been set to about 380 V during the experiment.

In the third stage, the prototype of TCR-based SVC is inserted to the system. The inductance value of the TCR-based SVC is 3.19 H and its capacitor value is 5 μF. The load voltage in this part is measured as 371 V after about 1 minute, as shown in Figure 9. Therefore, the measured load voltage is close to the nominal value. In the final part, the prototype of TCR-based SVC is removed from the test system, which has been fed by both the infinite bus and the generator. A load voltage of 348 V is approximately measured.

The power factor for the test system with the SMIB is given in Figure 10. A power factor of 0.65 lagging is obtained for the system without TCR-based SVC, while the power factor is measured as 1.0 in the system with TCR-based SVC. Thus, reactive power compensation is perfectly accomplished with TCR-based SVC.

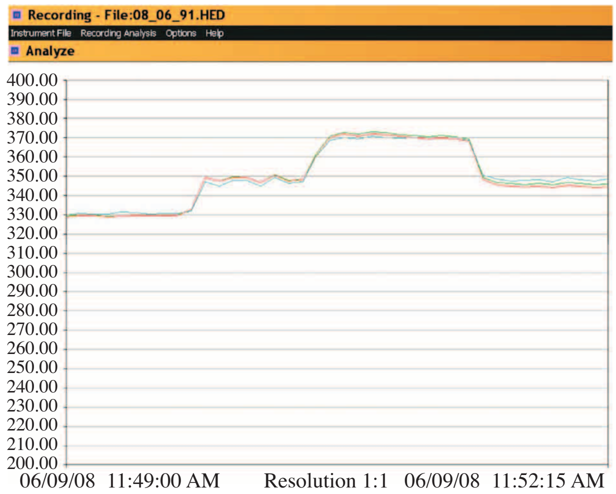

Figure 9. Load voltages for the system with the SMIB.

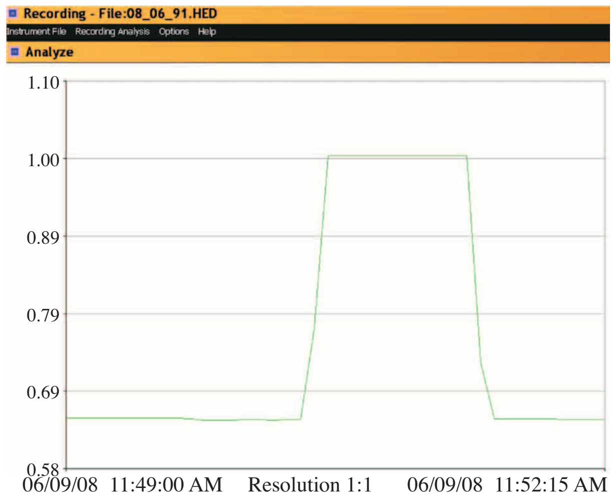

Figure 10. Power factor graphics for the system with the SMIB.

4. Conclusion

This paper presents the experimental studies of prototypes of TSR-based SVC and TCR-based SVC in the Power Systems Research Laboratory at Nigde University. The effects of TSR-based SVC and TCR-based SVC on load voltages have been studied in three-phase systems with a static load type. The power systems studied are a three-bus system with TSR-based SVC, and a SMIB system with TCR-based SVC. Experimental results show that significant improvement in reactive power compensation and load bus voltage regulation have been achieved by using TSR-based SVC and TCR-based SVC. For the SMIB system, successful results for reactive power compensation and voltage regulation have been obtained.

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