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ORIGINAL ARTICLE

Four-wire Solid State Transformer to Improve Current Quality

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ABSTRACT

Solid state transformers (SST) are used to perform typical functions and improve power quality in series operation of three-phase power systems. Generally, current harmonics and unbalances and neutral wire current are generated due to nonlinear, unbalance load and supply voltage distortion. In this paper operation of three-phase four-wire SST to improve current harmonics, current unbalances, neutral wire current and reactive power of nonlinear load as an active filter synchronous by feeding linear load is analyzed and application of AC/DC converter with four legs and it's controller to compensation of neutral wire current and current quality in the input stage of SST is investigated. Power quality improvement with SST has been verified by simulation results using MATLAB/SIMULINK. The results show that SST and its controller has very good performances, and it can not only realize the functions of series operation, but also can prevent from harmonics injecting and unbalances by parallel operation. Besides, proposed controller makes neutral wire current of voltage source becomes almost zero in four-wire distribution system.

Keywords: Four-wire solid state transformers, neutral wire current, Current harmonics and unbalances.

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1. INTRODUCTION

The Institute of Electrical and Electronic Engineers (IEEE) defines power quality as: “The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment.” [1]. Common power quality disturbances include surges, sag and swell in power source voltage and harmonics on the power line. Main factors of production current harmonics are nonlinear and time variant loads. The generation of harmonics and reactive power flow in a power system is greatly influenced by the widespread use of power electronic converters in addition to other sources of harmonics and reactive power. The distribution system may contain significant amounts of unbalanced load. Such loads produce large negative sequence and harmonic currents unequal distribution of single phase loads among phases and asynchronism and coincidence behaviour single phase loads are main factors of production unbalance and neutral wire current [1-7]. The unbalance load and excessive current in neutral wire is one of the issues in three phase four-wire distribution systems that causes voltage drop through neutral wire and makes tribulations for customers [5]. The levels of harmonic current flowing across the system impedance (which varies with frequency)

[♠] Corresponding author, e-mail: m.banaei@azaruniv.ac.ir determine the harmonic voltage distortion levels. Harmonics are caused by any device or equipment The existence of current harmonics and unbalanced load in power systems increases losses in the lines, occupation grid capacity, decreases the power factor and can cause timing errors in sensitive electronic equipments [6].

In recent years, using of power electronic converters to improve power quality in power distribution systems is the best solution, in terms of performance and stability, for the elimination of harmonic distortion, power factor correction, balancing of loads, and etc. Conventionally, passive filters were the choice for the elimination of harmonics and to improve power factor. These passive filters have the disadvantages such as large size, resonance and fixed compensation. Active power filters (APF) have demonstrated to be an interesting and effective solution to compensate current harmonics and reactive power in power distribution systems [8-13]. In [13], the performance of a grid connected photovoltaic (PV) system used as an active filter is presented. Its main feature is the capability to compensate the reactive and harmonic currents drawn by nonlinear loads while simultaneously injecting into the grid the maximum power available from the cells. The system can also operate as a standalone APF. Recently solid state transformers (SST) have been applied for voltage transformation and improving power quality of power systems. SST is a new type of transformer, which realizes voltage transformation and power delivery in a power system through power electronic conversion. Different topologies have been presented for realizing the SST, in recent years [14-24]. In [14], an AC/AC buck converter applies to reduce input voltage to a lower one. Another approach to realize SST structure is SST using high-frequency AC/AC link [15, 16]. They use the concept of a high-frequency AC/AC link, termed as power electronic transformer. One type is a three-part design that utilizes an input stage, an isolation stage, and an output stage. These types are called power electronic based transformer with DC-Link. Among SST structures, SST with DC-link is a new concept that enables to control and transfer power and can be employed to increase the power system flexibility. SST with DC-link enhances the flexibility and functionality of the electronic transformers owing to the available DC-links [17-25]. There are several types of SST with DC-link. In [17] a structure based on input series output-parallel connection of converters to realize SST structure is proposed. This scheme is extremely modular and performs power quality functions. In [18, 24, 25] a new topology based on cascaded multilevel converter has been introduced. It performs different power quality functions and prepares magnetic isolation but it needs many number of DC-link. In [20] a power transformer electronic with super capacitors storage energy system is proposed. The proposed system consists of a SST, a super capacitor bank and a bidirectional DC–DC converter. One type of SST with DC-link has been analyzed in [21]. This type of SST has less number of converter and DC-link. In [22] SST operation principle is analyzed and based on the analysis, the control scheme is established. Application of SST to power system and propose a new coordinated control strategy to improve the system stability by a generator-SST unit is proposed in [23].

which has nonlinear voltage-current characteristics.

Whole of SST structures have been used to feed loads in series state and operation of SST has been studied in different literature in series applications.

This paper investigates the SST that includes three parts: input stage, an isolation stage, and an output stage. In addition, application of AC/DC converter with four legs in the input stage is proposed and control method of this converter is analyzed. The presented system is able to compensating current harmonics, reactive power, current unbalance of nonlinear loads and neutral wire current side of voltage source when these loads are parallel with SST. In the other hands, synchronous by feeding special loads by SST, this transformer acts as active power filter. Neutral wire current of voltage source becomes almost zero by application of proposed control method to AC/DC converter with four legs. Power quality improvement with proposed power electronic transformer has been verified by the simulation results. All simulations are performed by using MATLAB/ SIMULINK.

2. SYSTEM DESCRIPTION AND OPERATION

SST with DC-link capacitor performs typical functions (isolation and transformation) and has advantages such as power factor correction, voltage regulation, voltage sag and swell elimination, voltage flicker reduction and protection capability in fault situations when the SST is series by load [17-23]. In the other hand power quality is improved by series operation of SST by load. In this paper, parallel operation of SST to compensate current harmonics and reactive power in four wire power distribution systems is discussed. The presented system is able to compensating current harmonics, reactive power, current unbalance of nonlinear load and voltage distortions. The basic configuration of case study is shown in Figure 1. The SST is used to provide an effective current control and to feed load.

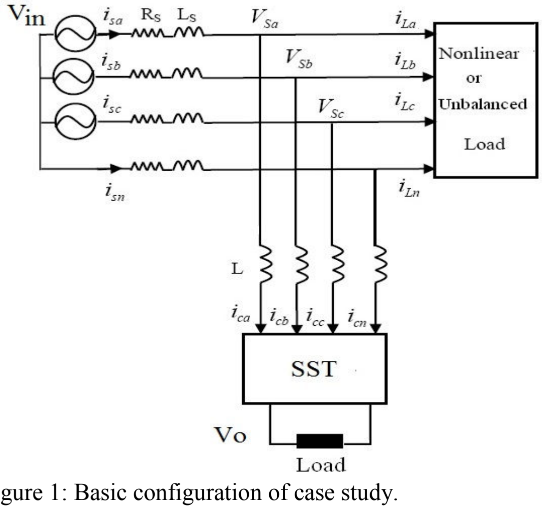


Figure 1: Basic configuration of case study.

The case study can be bring up: suppose industrial environment that linear, nonlinear and unbalance loads exist in it and one SST is used to feed some loads in this environment. Besides of main function to feed linear loads, this SST can be used as APF to compensate current quality.

Figure 2 shows a typical actual circuit diagram of SST with DC-link, which is used of case study. This transformer generates the compensating currents to compensate the load currents, in order to guarantee sinusoidal, balanced, compensated currents drawn from the AC system. As can be seen from Figure 2, this is a three-stage design that includes an input stage, an isolation stage and an output stage.

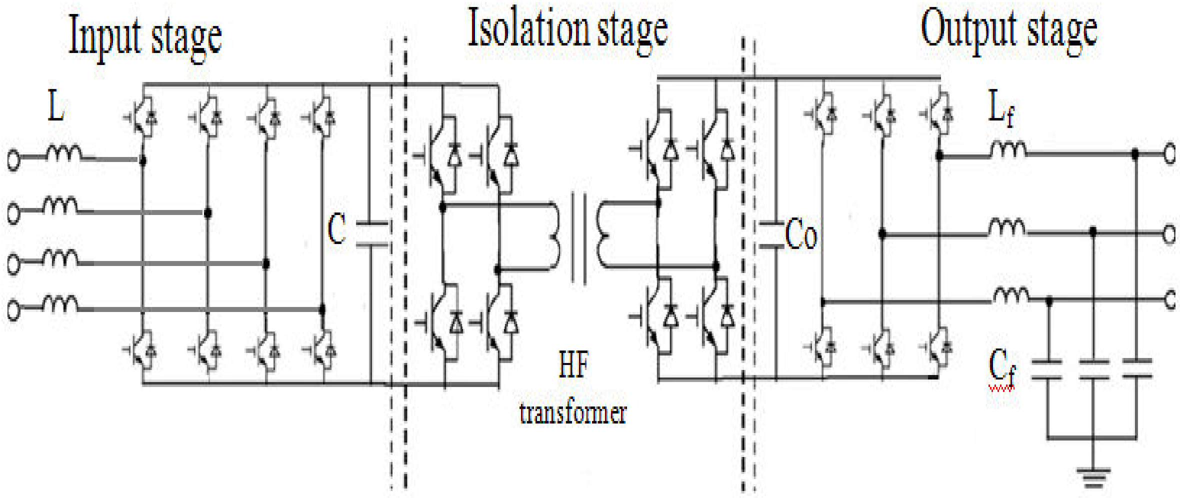


Figure 2: Circuit diagram of SST.

In the input stage, there is a converter, which converts the input AC voltages to DC voltage. The isolation stage consists of two H-bridge converter and HF transformer. The isolation stage is DC/DC converter. In the output stage, there is a three-phase converter, which converts the DC voltage from the isolation stage to three phase AC sinusoidal voltages. The SST has three stages and each stage can be controlled independently from the other one. Many advantages of the SST such as power quality depend on appropriate close-loop control [21-23].

First stage is an AC/DC converter which is utilized to shape the input current, to correct the input power factor, and to regulate the voltage of primary DC-link. Figure 3 shows connection of input stage and case study system. The input stage is a three phase rectifier, which is used to convert the primary low frequency voltage into the DC voltage. The main functions associated with the rectifier control are shaping the input current, controlling the input power factor and keeping the DC-link voltage at the desired reference value. The AC/DC converter is connected in parallel with the three-phase supply through three inductors. The DC side of the AC/DC converter is connected to a DC capacitor, C, that carries the input ripple current of the converter and the main reactive energy storage element. The DC capacitor provides a constant DC voltage and the real power necessary to cover the losses of the system. The inductors perform the voltage boost operation in combination with the capacitor, and at the same time act as the low pass filter for the AC source current. Then the AC/DC converter must be controlled to produce the compensating currents.

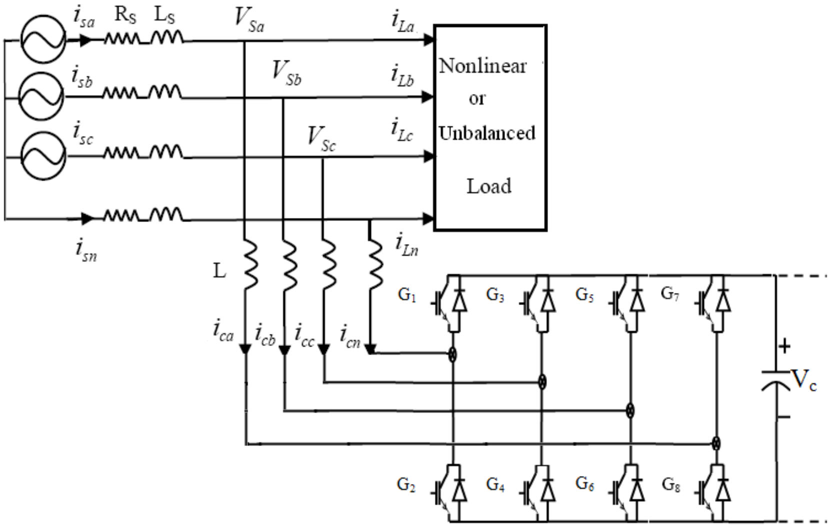


Figure 3: Connection of input stage and case study system.

Many control methods are presented for control of input stage in SST [19-21] or in active power filters [8-13], which could be used in proposed system. The quality and performance of the SST depend mainly on the method implemented to generate the compensating reference currents. This paper presented a method to get the reference current, which is key issue in the control of the SST. This method is used in active power filters [10, 12] but in this paper its expanded for SST.

The basic function of the proposed system is to eliminate harmonics and compensation of current unbalance, reactive power of load and voltage source distortion. The basic operation of this proposed control method is shown in Figure 4. The estimation of the reference currents for AC source is the basic idea in control system. The peak of source reference current has two components. The first component is corresponding to the average load active power and the second component of AC source current is obtained from DC capacitor voltage regulator. The capacitor voltage is compared with its reference value, V_C, in order to maintain the energy stored in the capacitor constant. The PI controller is applied to regulate the error between the capacitor voltage and its reference. The three-phase compensating reference current of SST are estimated using reference supply currents and sensed load currents. The compensating currents of SST are calculated by sensing the load currents, DC-link voltage, peak voltage of AC source (V_{sm}) and zero crossing point of source voltage. The last two parameters are used for calculation of instantaneous voltages of AC source as below:

$$V_{Sa} = V_{Sm}\sin(\omega t)$$

$$V_{Sb} = V_{Sm}\sin(\omega t - 2\pi/3) \qquad (1)$$

$$V_{Sc} = V_{Sm}\sin(\omega t + 2\pi/3)$$

Three phase locked loop (PLL) is used to calculate frequency or angle velocity (ω).The sum of two components peak of source reference current is multiplied by the mains voltage waveform V_{Sa}, V_{Sb} and V_{Sc} in order to obtain the supply reference currents, i_{Sref} for three phase. Then the supply reference currents are proportional to the mains voltages. The supply reference current for neutral wire is zero. The reference currents of SST can be obtained from difference of i_{sref} and i_{nL}. The reference signals for converter switching in input stage are obtained from comparison between reference currents of SST and currents of SST. The conventional hysteresis band current control scheme is used for the control of input stage. The reference signals for converter switching are presented as equation 2.

$$e = i_{cref} - i_c \qquad (2)$$

The hysteresis band current controller decides the switching pattern of input stage. The switching logic is formulated as follows:

If ea>0.001 then upper switch is OFF and lower switch is ON for leg “a” (G_8=1).
If ea<-0.001 then upper switch is ON and lower switch is OFF for leg “a” (G_7=1).

The switching functions for phases B, C and neutral wire are determined similarly.

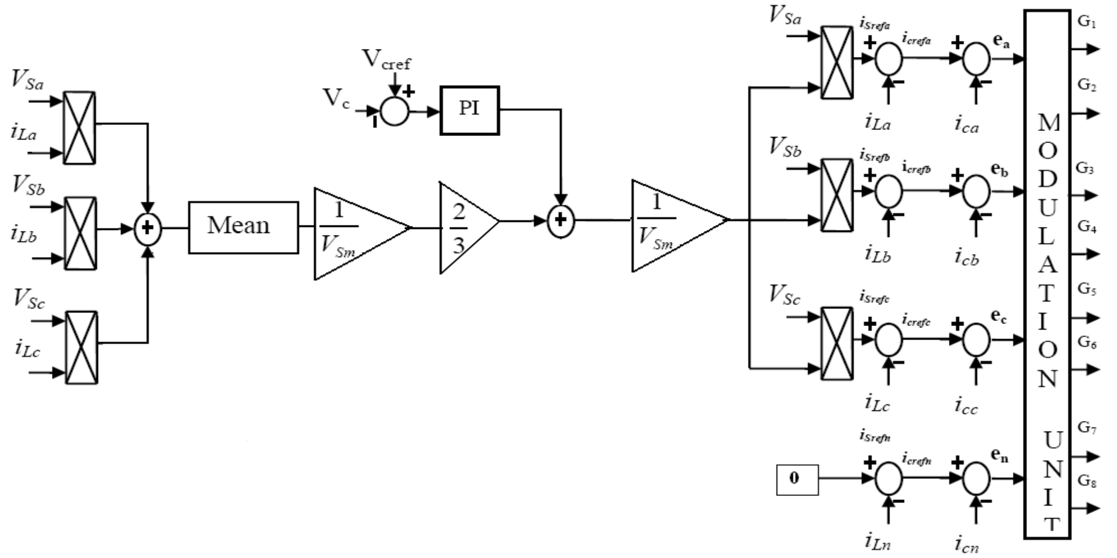


Figure 4: Input stage control diagram

Second stage is an isolation stage which provides the galvanic isolation between the primary and secondary side and converts the input DC voltage to DC voltage. Isolation stage is contained two single-phase high frequency voltage source converter (VSC) and HF (MF) transformer. The main functions of the HF (MF) transformer are such as: voltage transformation and isolation between source and load. Structure of the isolation stage is shown in Figure 5. To simplify the design of the control system, open loop control is applied for the VSCs. By neglecting the losses of HF (MF) transformer, the HF (MF) transformer can be treated as a proportional amplifier [21-23]. The simplified model of the MF transformer is presented as:

$$V_2 = \frac{N_2}{N_1} V_1 \tag{4}$$

V_1, V_2 are the primary and secondary voltage in HF (MF) transformer, respectively and N points to turn ratio. A DC voltage source can be generated by isolation stage that is used in output stage.

Figure 6 shows output stage of SST. Three levels voltage source inverter topology converts DC voltage to a power frequency three- phase output. This converter generates desired output voltage with suitable shape and frequency. As it can be seen in Figure 7, the output inverter is controlled by pulse widths modulation (PWM) method. In this case, the direct axis, quadratic axis, and zero sequence quantities for three-phase sinusoidal signal is computed by Park transformation. Then the dq voltage terms are compared by reference signals V_{dref} and V_{qref} and error signals enter to PI controllers. Next the PI controller outputs are transformed to three-phase sinusoidal abc voltage terms and used to generate appropriate inverter gate pulses.

If connected load to SST changes, input stage controller makes to keep constant voltage of DC-link capacitor (Vc). Despite of the voltage ripple on the DC-link, the SST will operate properly because the output block of SST, DC/AC converter, will eliminate the voltage ripple by proper variation of modulation.

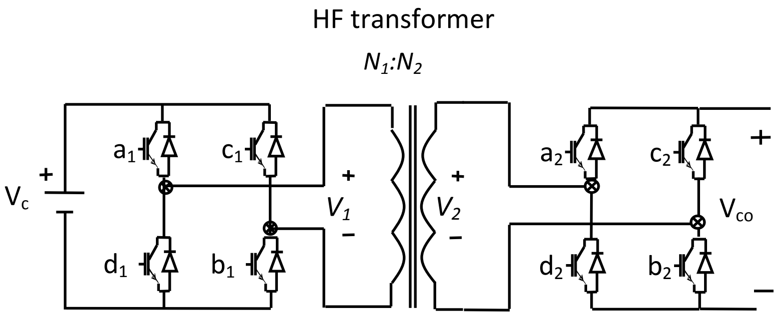


Figure 5: Structure of the proposed isolation stage.

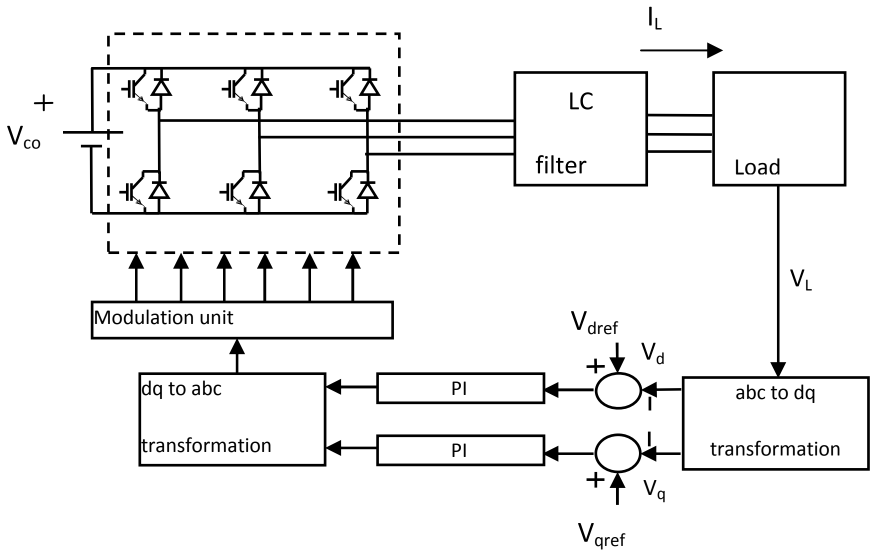


Figure 6: Circuit control of output stage.

3. SIMULATION RESULTS

The analysis of the three-phase four wire system given in Figure1 has been done in SIMULINK/ MATLAB environment. The system has a 3-phase AC source of 380 V at 50 Hz feeding a 3-phase nonlinear unbalanced load and RL load by SST.

A number of simulation results with different operating conditions were developed. In Figure 7, SST is connected in parallel with nonlinear load. Table 1 shows the case study parameters. The nonlinear load configuration is described in Figure 7.

Table 1: Parameters of case study

Parameters	Value
Input line voltage	380 V
Source resistance and inductance	0.3 Ω, 0.6 mH
Power frequency	50 Hz
MF transformer	1:1, 1000 Hz, 30 kVA
Output line voltage	380 V
L, C (input stage)	0.9 mH, 1000 µF
LC filter	2 mH, 220 µF
SST Load	20 kW+j10 kVAR

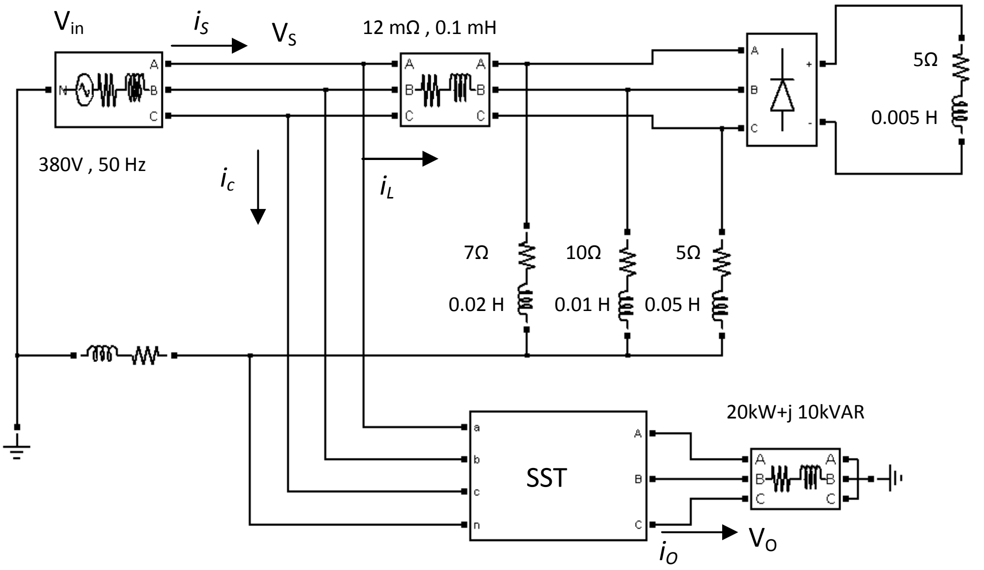
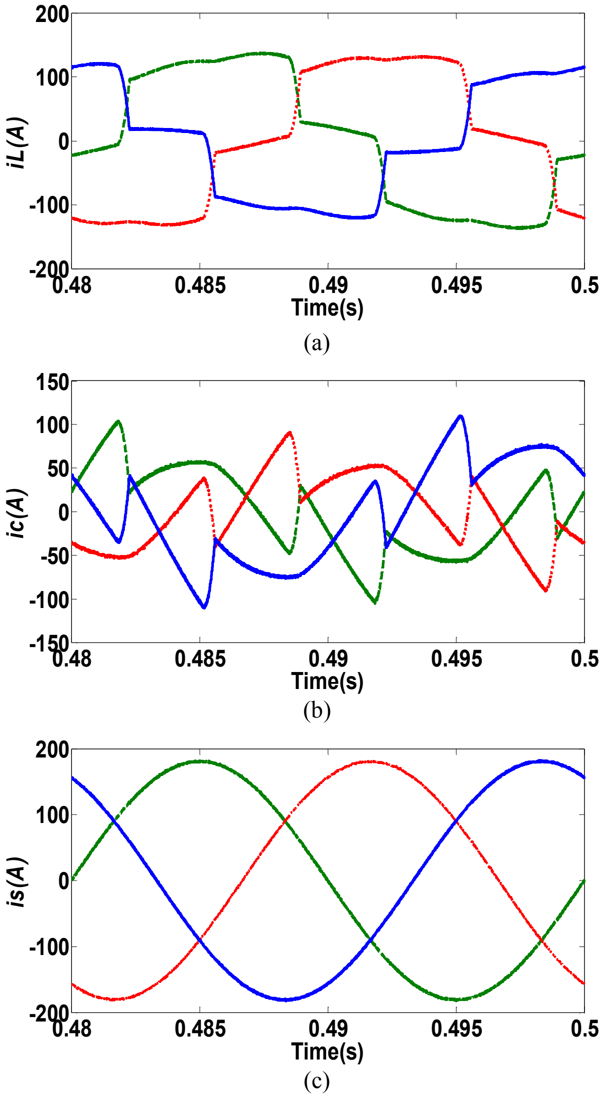


Figure 7: Parallel connection of SST and non linear load.

In this simulation, the nonlinear unbalanced load is considered a 3-phase diode rectifier and a three phase unbalance load. Two operative conditions have been considered. The simulation results in steady state operation are presented. Figure 8 shows the performance of the SST system using PI controller. Current of the nonlinear load is shown in Figure 8(a). You can see that the three phase currents are seriously unbalanced and the waveforms are distorted. Figure 8(b) shows the SST current. SST current consists of harmonic compensation current and series load current. Supply current is shown in Figure 8(c) that is sinusoidal and balance current. Figure 9 shows the supply, nonlinear load and SST load currents superimposed to the supply voltage. In other hand power factor correction is shown in this figure. Figure 10(a) reveals the harmonic spectrum of load current. Figure 10(b) describes the harmonic spectrum of supply current. Using spectrum analysis we find a THD of the A phase current of 22.03%. It can be observed from the harmonic spectrum of currents that, presented structure is effective to obtain desired harmonic level. Figure 11 shows neutral wire currents. The neutral wire current side of unbalanced load is very big but the neutral wire current side of voltage source is very small. The input currents in the three phases after compensation are expected to be purely sinusoidal and in phase with the mains voltages, also note that the neutral wire current equal to approximately zero. The SST load voltage and current are shown in Figure 12(a) and 12(b), respectively.



(a)

(b)

(c)

Figure 8: (a) Nonlinear unbalanced load current (b) SST current and (c) supply current.

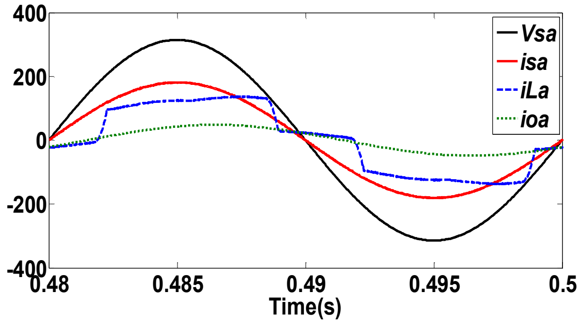
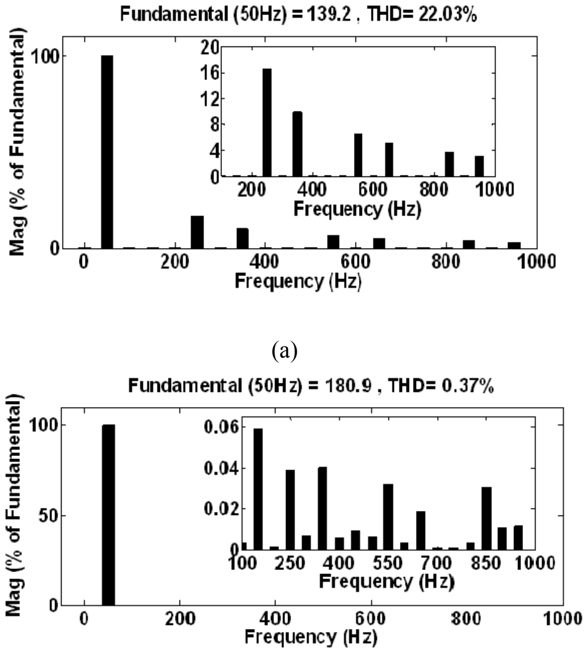


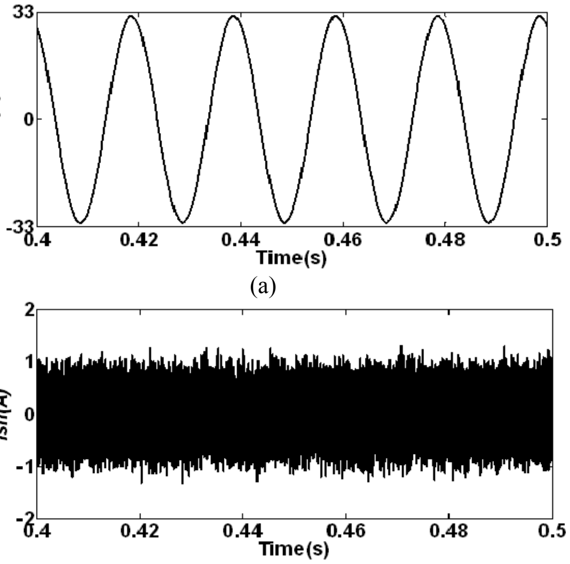
Figure 9: Supply, SST load and non linear load currents superimposed to the supply voltage.



(a)

(b)

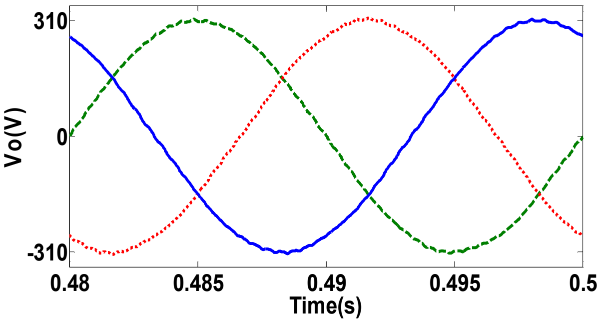
Figure 10: (a) Harmonic spectrum of load current and (b) Harmonic spectrum of supply current.



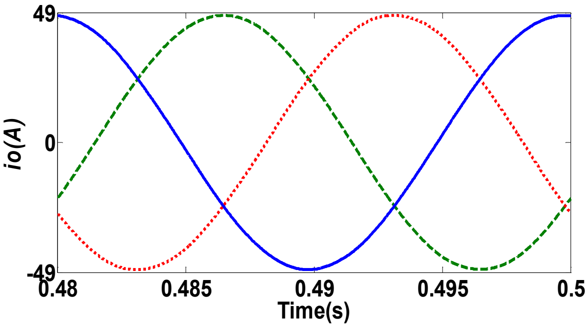
(a)

(b)

Figure 11. Neutral wire current side of unbalanced load waveform and (b) Neutral wire current side of suplly source.



(a)



(b)

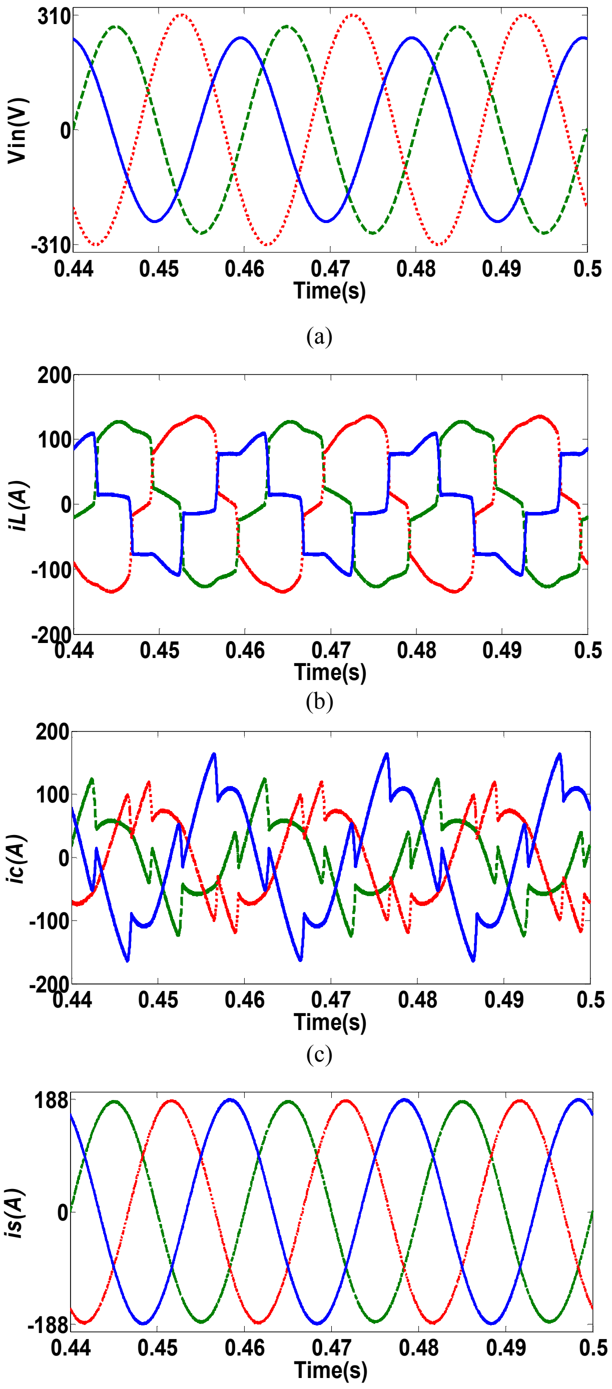
Figure 12: (a) SST load voltage and (b) SST load current.

In second group of simulation compensation of input currents in voltage source distortion state are shown. Figure 13(a) shows supply voltage. Voltages of supply are given as:

$$V_{ina} = 0.9 * 310.26\sin(\omega t)$$
$$V_{inb} = 310.26\sin(\omega t - 2\pi/3 - \pi/10) \qquad (5)$$
$$V_{inc} = 0.8 * 310.26\sin(\omega t - 4\pi/3 - \pi/8)$$

Currents of the nonlinear load, SST and supply are shown in Figure 13(b), (c) and (d). The nonlinear current and input voltages are unbalanced. SST injects current to balance supply currents. These results show that supply currents always remain sinusoidal and balanced.

The presented simulation results show the validity and effectiveness of presented structure system in power quality improvement by parallel operation of SST to compensate current harmonics, unbalance currents, voltage source distortion and reactive power in power distribution systems. In series operation of SST whole loads currents pass from among SST converters but in parallel operation less part of whole loads currents pass from among SST converters.



(a)

(b)

(c)

(d)

Figure 13: (a) supply voltage (b) Nonlinear unbalanced load (c) SST and (d) supply currents.

4. CONCLUSIONS

In this paper parallel operation of power electronic transformer with DC-Link capacitor with non linear unbalanced load in four wire system is studied. Power electronic transformer improved power quality and perform the primary functions, such as voltage transformation, isolation and feeding load. In addition, compensating current harmonics, reactive power and current unbalance of nonlinear loads by parallel operation of power electronic transformer with DC-Link capacitor have been shown in this paper. The simulation results show that the three phase current waveforms are generally balance and the THD is very small. Neutral wire current after compensation equal to approximately zero.

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