SHUNT ACTIVE FILTER FOR HARMONIC MITIGATION OF A RESISTAN CE SPOT WELDING MACHINE

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Abstract:

This paper introduces a design and simulation of an adaptive shunt active filter (SAF) for harmonic mitigation of a resistance spot welder RSW. This type of welding machines causes unacceptable current distortions in the utility electrical distribution system, especially when an adjacent manufacturing facility with extensive electronic controls exists. This paper demonstrates effective use of active low-pass filter with the PWM carrier strategy to control the current of active filter. The method is based on frequency domain. In this study, a model of a typical power system coupled with RSW is presented. The studied system and the active filter are implemented in PSIM software, representative waveforms and spectral analysis is presented, simulation results show that the proposed active filter is very effective in harmonic elimination of the RSW.

Keywords: *Active power filter, resistance spot welder, low-pass filter, harmonic mitigation techniques and power quality.*

1. Introduction

Nowadays, many industries prefer to use power electronics based devices due to their effectiveness and robustness. Though these power electronics based devices are advantageous to the electronics and electrical industry, they generate and inject unfavorable harmonics in the power grids. Power quality is very important to commercial and industrial power system designs. Ideally, the power supply should be a pure sine wave with no any type of distortion. If the voltage /or current waveforms are distorted from its perfect shape, it will be described as harmonic distortion [1].

The most common sources of harmonic include motor starters, variable speed drives, electronic loads, discharge lighting, arcing equipment, welding machines and uninterrupted power supplies [2].

Electric welding is generally an economical and efficient means of joining metals permanently. Different welding methods are used commercially and can be classified into: Forge welding, Thermite welding, Gas welding, Arc welding and Resistance welding [3]. Resistance spot welding (RSW) is cheap and effective method of connecting metals. It has many applications in home appliances and in automobile industry [3]. This machine has a front-end diode rectifier for AC/DC power conversion, IGBT inverter, and medium frequency transformer. The working frequency is about 1 KHz, while the typical power supply frequency is 50 or 60Hz, based on the region. Therefore, input current of the RSW inverter contains higher content of low-order harmonics which have undesirable impacts on distribution power system and causes malfunction of other equipment connected in the nearby. With the presence of harmonics, generators and power transformers experience extra heating in the phase winding and hence, additional power losses are appeared in such electrical equipment [4].

In order to reduce the problems arising from welding machines some standards and recommendations have been developed. IEEE Std. 519-1992 is the most commonly criterion used for harmonic pollution limit [5-6].To avoid extreme cases, the effective elimination of harmonics from the distribution system has become important for the utilities and the customers.

There are set of traditional solutions to the harmonic distortion problems which have existed for a long time. These solutions include line reactors, phase multiplication, and passive filters [7-11].

Recently, researchers were encouraged to develop modern, adaptable, and more effective solutions for harmonics problems. These modern solutions have been given of active power filters (APFs). One of the most common active filters is the shunt active filter (SAF) [12-15]. This filter is connected in parallel with the non-linear loads. Conventionally, a SAF is designed to cancel harmonics and to inject reactive components at the point of common coupling (PCC). The main target here is to compensate for current harmonics of RSW very effectively. The active low-pass filter has been used for generating the reference current which should be followed by active filter. The grid model coupled with RSW and designed filters are simulated using PSIM software. Understanding the properties of the harmonic emissions caused by RSW loads presents valuable data to welder manufacturers, and hence, welder design modifications can be considered to comply with power quality standards.

2. Studied System Configuration

The system under study in this work is shown in Fig. 1. It consists of utility 132 KV bus-bar, and steps down the voltage to 11 KV through a 12000 KVA, 138/11 KV 8% reactance transformer. Several existing 11KV overhead distribution circuits provides power to the local residents and industries. An overhead distribution circuit 11kV called the "shared line" will serve an adjacent customer with extensive electronic controls as well as the RSW under study. A service transformer of 100KVA, 11/0.38 KV and 4% resistance is supplying the RSW and house load. The maximum load of the RSW is 150 A at 380 V.

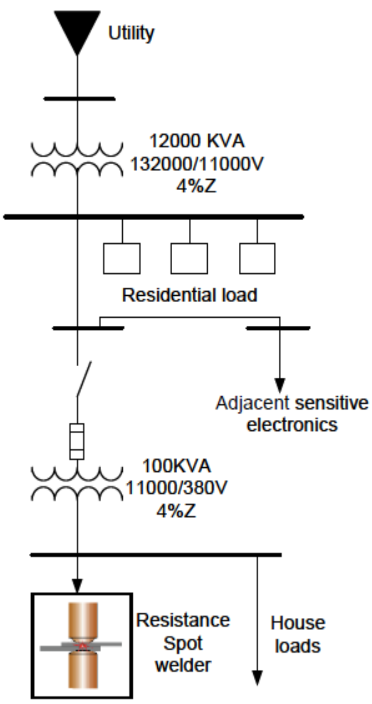

Fig.1. The configuration of the system under study.

2.1 Resistance Spot Welder

The main circuit diagram of the RSW consists of the following: three phase AC supply unit, a rectifier unit which rectifies the input voltage and stores energy in the capacitor bank after this, there is an inverter unit operated at a medium frequency of 1000 Hz, and the welding electrodes. The inverter circuit connected to a single phase transformer, which steps down the voltage and steps up the current. The transformer has two secondary windings and a full wave rectifier mounted on it to ensure a short rise time for the welding current. This high frequency voltage from the output of the inverter allows reducing the size of the bulky transformer as compared to that of the traditional 50Hz transformer. The rectified output is then delivered to the welding electrodes.

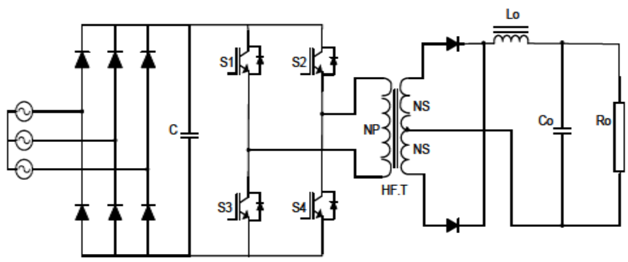

Fig. 2. Circuit diagram of a typical resistance spot welder.

3.Problem Description

The RSW machine has a front-end diode rectifier for AC/DC power conversion, IGBT inverter, and medium frequency transformer. The working frequency is about 1 KHz, while the typical power supply frequency is 50 or 60Hz, based on the region. Therefore, input current of the RSW inverter contains a higher content of low-order harmonics which have undesirable impacts on the distribution power system and causes a malfunction of other equipment connected with the nearby. Power system voltage and current waveforms can be represented using harmonic components of Fourier series [17], as follows:

$$V_T = \sqrt{2}\, V_1 \sin(\omega_0 t - \theta_{v1}) + \sum_{h=1}^{\infty} \sqrt{2}\, V_h \sin(h\omega_0 t - \theta_{vh}) \quad (1)$$

$$I_T = \sqrt{2}\, I_1 \sin(\omega_0 t - \theta_{i1}) + \sum_{h=1}^{\infty} \sqrt{2}\, i_h \sin(h\omega_0 t - \theta_{ih}) \quad (2)$$

Where **h** is order of harmonic. $\mathbf{V_1}$ and $\mathbf{I_1}$ are the voltage and current r.m.s values of the fundamental component. $\mathbf{V_h}$ and $\mathbf{I_h}$ are the voltage and current r.m.s values of the h^{th} harmonic order. $\mathbf{\Theta_{v1}}$ and $\mathbf{\Theta_{i1}}$ are voltage and current phase angle of the fundamental component. $\mathbf{\Theta_{vh}}$ and $\mathbf{\Theta_{ih}}$ are the voltage and current phase angle of the h^{th} harmonic order. $\boldsymbol{\omega_0}$ is the fundamental angular frequency.

The most common standard used for measuring harmonics is Total Harmonic Distortion (THD) [18].

$$VTHD = \frac{1}{V_1}\sqrt{\sum_{\infty}^{h=2} V_h^2} \times 100 \quad (3)$$

$$ITHD = \frac{1}{I_1}\sqrt{\sum_{\infty}^{h=2} I_h^2} \times 100 \quad (4)$$

Where VTHD and ITHD are THD values for current and voltage, respectively, and V1, I1 are the voltage and current r.m.s. values of the fundamental frequency, respectively. The presence of harmonic distortion in the utility system results in many problems in the operation of the system. This problem can be categorized to include the following:

A- Increased energy losses in the following:
1. Cable supplying nonlinear loads
2. Utility transformers and generators supplying the polluted network
3. Motors supplied by the polluted network

B- Accelerated aging of equipment due to heat in the following:
1. Transformer
2. Rotating Machine
3. Switchgear
4. Phase and neutral conductors
5. Capacitor banks
6. Lighting devices

C- Malfunctions of equipment due to harmonic effects in the following:
1. Protective relays
2. Metering devices
3. Electronic Equipment

Effect to limit harmonic distortion to acceptable proportions is a concern for power engineers. Standards relating to harmonics are laid down by the IEEE 519 Standard. To define current distortion limits, IEEE Std 519 uses a short circuit ratio to establish a customer size and potential influence on the voltage distortion of the system. The short circuit ratio (ISC/IL) is the ratio of short circuit current (ISC) at the point of common coupling with the utility, to the customer's maximum load or demand current (IL) [5].

Table 1. IEEE 519 current distortion Limits (in % of IL) for General Distribution Systems (120- 69,000V).

I_{sc}/I_L	h < 11	11≤ h <17	17≤ h <23	23≤ h <35	35≤ h
<20	4.0	2.0	1.5	0.6	0.3
20-50	7.0	3.5	2.5	1.0	0.5
50-100	10.0	4.5	4.0	1.5	0.7
100-1000	12.0	5.5	5.0	2.0	1.0
>1000	15.0	7.0	6.0	2.5	1.4

Where:
I_{SC} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

In this paper the short circuit ratio is 84, that means the maximum allowable total harmonic distortion of the current is 12%.

4. Solutions for the Harmonics

Various harmonic reduction methods have been developed to guarantee staying harmonic voltage and current within reasonable limits. Generally, these methods can be classified into: line reactors, phase multiplication systems (12-pulse, 18-pulse systems), passive filters, and active filters.

4.1 Line Reactors

A line reactor is a three-phase series inductance on the line side of a nonlinear load; the reactor makes the current waveform less deformation resulting in lower current harmonics. Note that the reactor impedance increases with frequency; it provides high impedance to flow of higher order harmonic currents. The advantages of using line reactors include low cost, moderate reduction in voltage and current harmonics, availability in various values of percent impedance and increased input protection for its semiconductors from line transients. The disadvantage may not always reduce harmonic levels to below IEEE Std.519-1992 guidelines and need to handle the full current of the load.

4.2 Phase Multiplication Systems (12-pulse, 18-pulse systems)

Phase multiplication solutions tracking using a multi-winding transformer with phase angle in the windings. A 12-pulse system uses two secondary windings and 18-pulse system use three secondary windings. The phase angle degrees between every secondary winding are 360 divided by the number of system pulses. The harmonic orders produced on the power system written as $h = p * k \pm 1$ where p is the number of pulses and k is 0,1,2.. A 12-pulse system will have lowest harmonic order of 11, similarly, a 18-pulse system will have a harmonic spectrum being from the 17th harmonic and highest. The advantage of using phase multiplication systems is significantly reduced current distortion, but the disadvantages involve Sensitive to voltage unbalance, non-flexible, size big and heavy.

4.3 Passive Filters

Passive filters consist of passive elements like inductors, capacitors and resistors. The filter is tuned to a frequency at which inductive and capacitive reactance are equal. Undesirable harmonic current may be prevented by one of two methods, use of high series filters impedance to block them or by diverting them by means of a low impedance shunt passive filter paths. The advantages of using a passive filter to include low cost and it is easy tuning at the specific frequency. This filter has some negatives that the filtering characteristics dependent on the source impedance, not appropriate for changeful loads, there is a parallel resonance and has large configuration size.

4.4 Active Filters

The active filter concept uses power electronic circuit to produce current and voltage components that cancel the harmonic currents and harmonic voltages produced due to the non-linear loads. Parallel (or shunt) active filter has been recognized as a valid solution to current harmonic suppression and to reactive power compensation of non-linear loads. Series active harmonic filters are another type of filters uses for voltage harmonic suppression and for boosting series voltage to the 50HZ components. In comparison to conventional passive filters, active filter offer very fast control response, more flexibility, reduction of system losses and reduction of harmonic levels to below IEEE Std.519-1992. The objective of this study is to reduce the harmonic distortion of the current absorbed by RSW loads, the shunt active filter is more appropriate.

4.4.1 Description of the Proposed Shunt Active Filter (SAF)

The basic compensation principle of the SAF is to control the filter current in a closed loop control to generating a harmonic that is conversational in phase of the distorted distorted harmonic current to make sinusoidal source current and also correct the supply side power factor as shown in Figure (5).

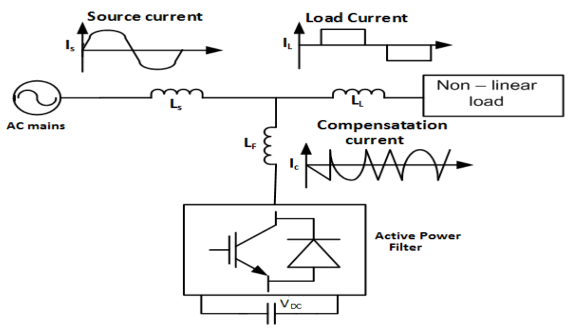

Fig.5 schematic diagram of the nonlinear load with shunt active filter

The proposed SAF consists of

- A power inverter circuit (VSI).
- DC capacitor (Cdc).
- Smoothing inductor (L_f).
- Smoothing high frequency filter capacitors (C_f).
- Active low –Pass filter.

The voltage source inverter (VSI) consist of six power switches in a single three-phase full-bridge configuration, with anti-parallel diodes connected to the DC capacitor located at the bus of the switches. The DC capacitor serves as an energy storage element for providing a constant DC voltage for real power necessary to cover the SAF losses at steady state. The purpose of the filter inductor, (Lm) is to regulate the maximum allowable magnitude ripple current flow into the SAF. The filter capacitance (CF) is used to mitigate the high-frequency ripple components and thus reducing the switching stress on the SAF switches. The active low-pass filter has been used for generating the reference currents which should be followed by active filter.

4.4.2 Proposed SAF Control Circuit

The load current of the RSW which consists of fundamental and harmonics is taken through two second order low-pass filters connected in cascade for generating the fundamental currents (I_{af}, I_{bf}, and I_{cf}) in three phase, which should be followed by active filter, the output of the low-pass filter the fundamental component with phase shift 180° is obtained, so we should use inverted amplifier. The reference currents to the APF per phase,(I^*_{fa}, I^*_{fb} and I^*_{fc}) are determined by the subtraction of non-linear currents (I_{Nfa}, I_{Nfb}, and I_{Nfc}) and the fundamental current by subtractor circuit.

$$I^*_{fa} = I_{Nfa} - I_{af}$$
$$I^*_{fb} = I_{Nfb} - I_{bf}$$
$$I^*_{fc} = I_{Nfc} - I_{cf}$$

The output of subtractor is taken to a proportional integration PI controller, which compares the actual value of harmonizing with the desired value and produces a control signal which will reduce the deviation to zero or to a small value. Then this signal is passed through the voltage limiter circuit. The output of the voltage limiter circuit is taken to the input terminal of a comparator and other high-frequency triangular wave is taken to the other input of the comparator. The output of comparator circuit is the desired switching signal for the inverter. The control signal operates the inverter i.e. turns on or off the IGBTs to get the compensating current.

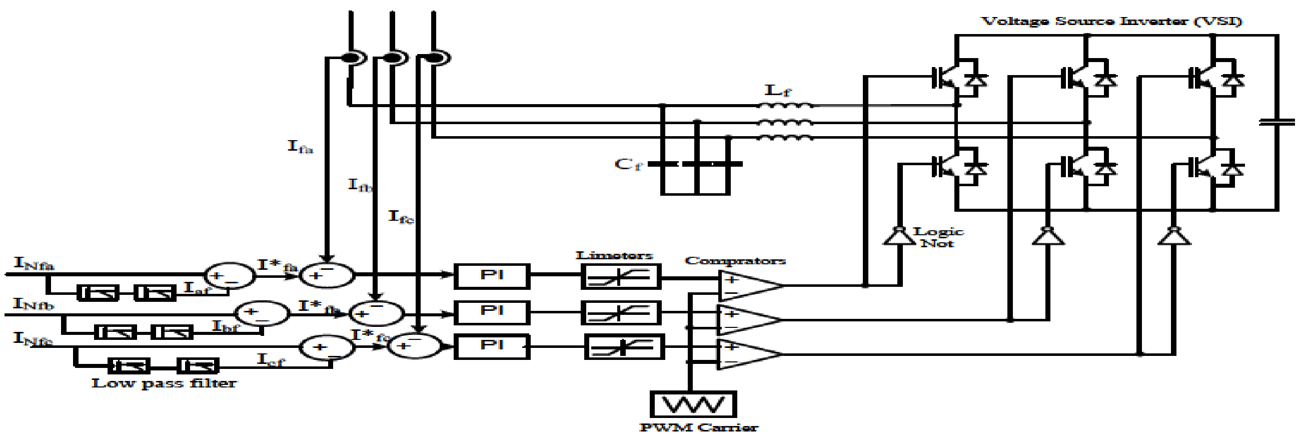

Fig. 6. control circuit of the proposed SAF

5. Simulation Results

In this section the results of two case for the RSW are simulated and analyzed: a) before filtering , b) after using SAF.

5.1 Results Before Filtering

The system model as illustrated in fig.(7) consist of fundamental supply voltage at MV side connected to the power transformer through MV cable with resistance and inductance. The low voltage side of transformer LV is connected RSW through LV cable with resistance and inductance. The voltage and current waveforms (only one phase current has been shown for the clearness) and their frequency spectrum at LV and MV side before filtering are illustrated in Figs. (8-11). The THD of current is 80.03% at MV side and 87.287% at LV side before filtering.

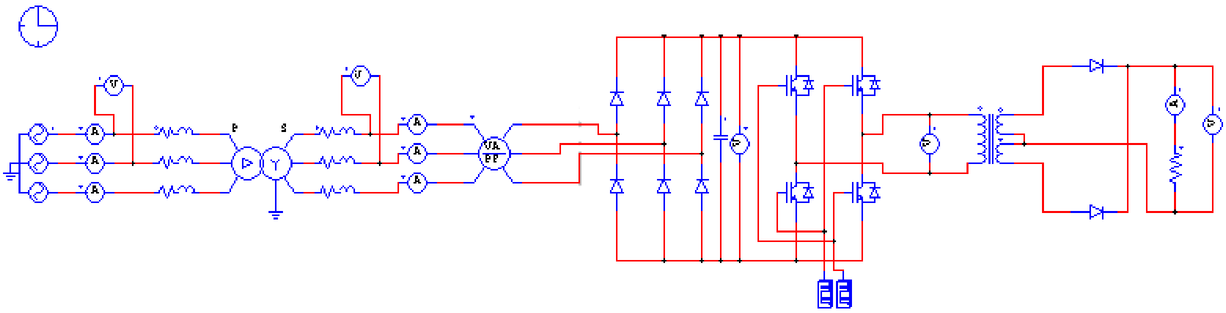

Fig.7. Simulation model of the RSW

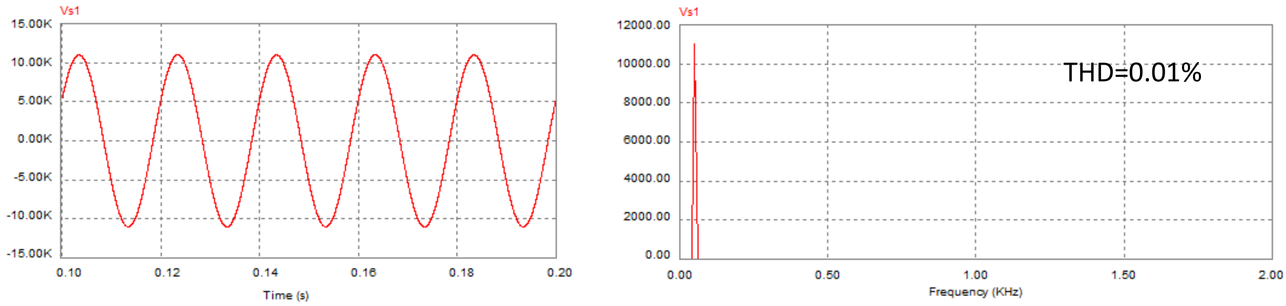

Fig.8. Voltage waveforms and its frequency spectrum at MV side before using SAF

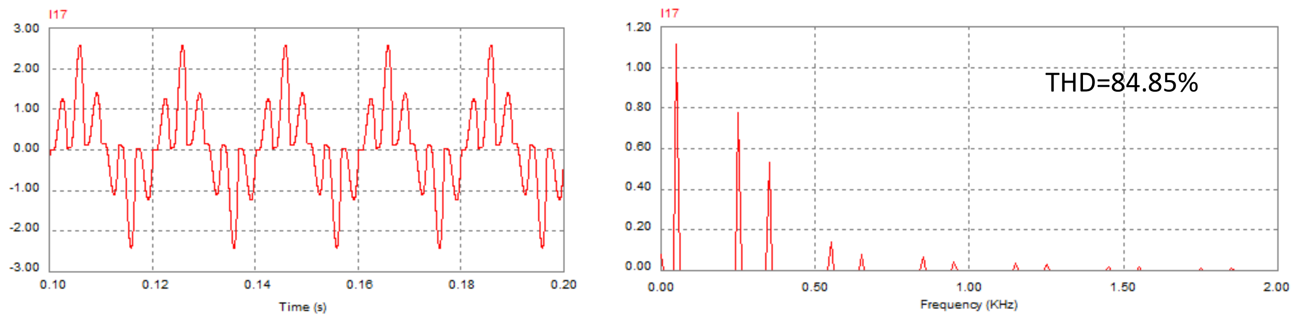

Fig.9. Current waveforms and its frequency spectrum at MV side before using SAF

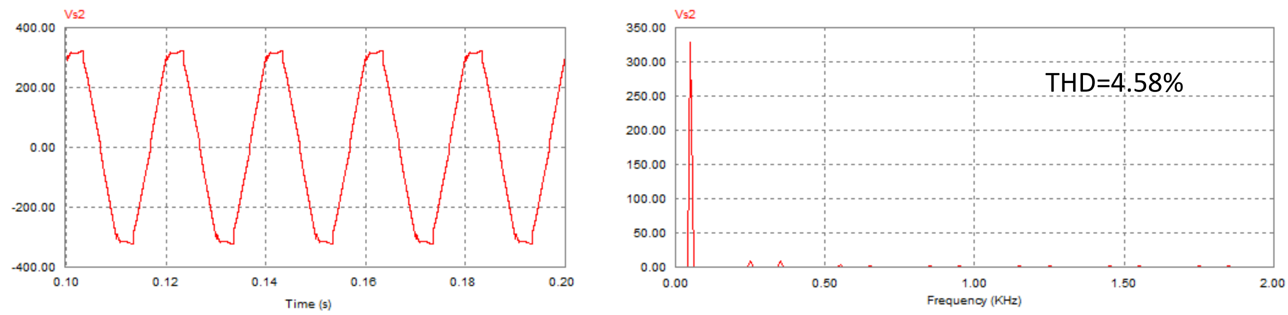

Fig.10. Voltage waveforms and its frequency spectrum of LV side before using SAF

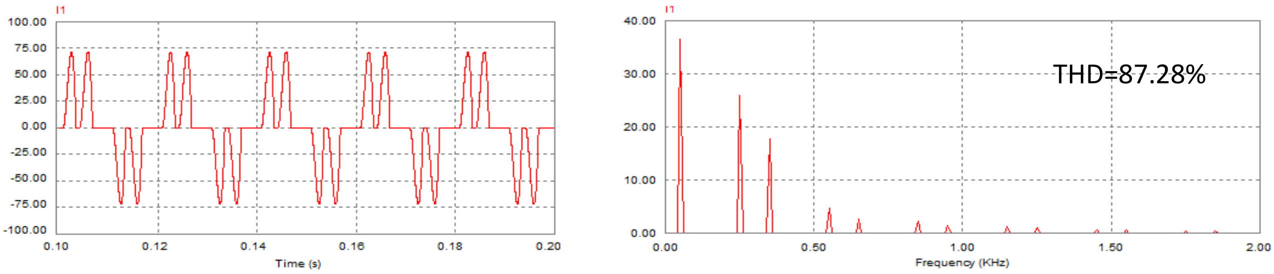

Fig.11. Current waveforms and its frequency spectrum of LV side before using SAF

5.2 Simulation Results after Using SAF

Table 2 is a summary of the parameter of APF values. Fig 11. Shows the simulation model of RSW after using SAF. Voltage and current waveforms (only one phase current has been shown for the clearness) and their frequency spectrum at LV and MV after using SAF are illustrated in Figs.(13-16), the compensating current of SAF illustrated in fig.17.

Table 2. Design parameters of the SAF

Parameter	**Value**
Inductor Filter (LF)	1mH
Capacitor Filter (CF)	1000μF
PWM Carrier frequency (FPWM)	10KHZ
SAF DC Voltage (VDC)	1500V
Cut-off frequency of low- pass filter	50HZ
Low -pass filter damping ratio	0.1
Inverted amplifier resistances	10kΩ
Time constant PI controller	0.001
Frequency triangular signal	10KHZ

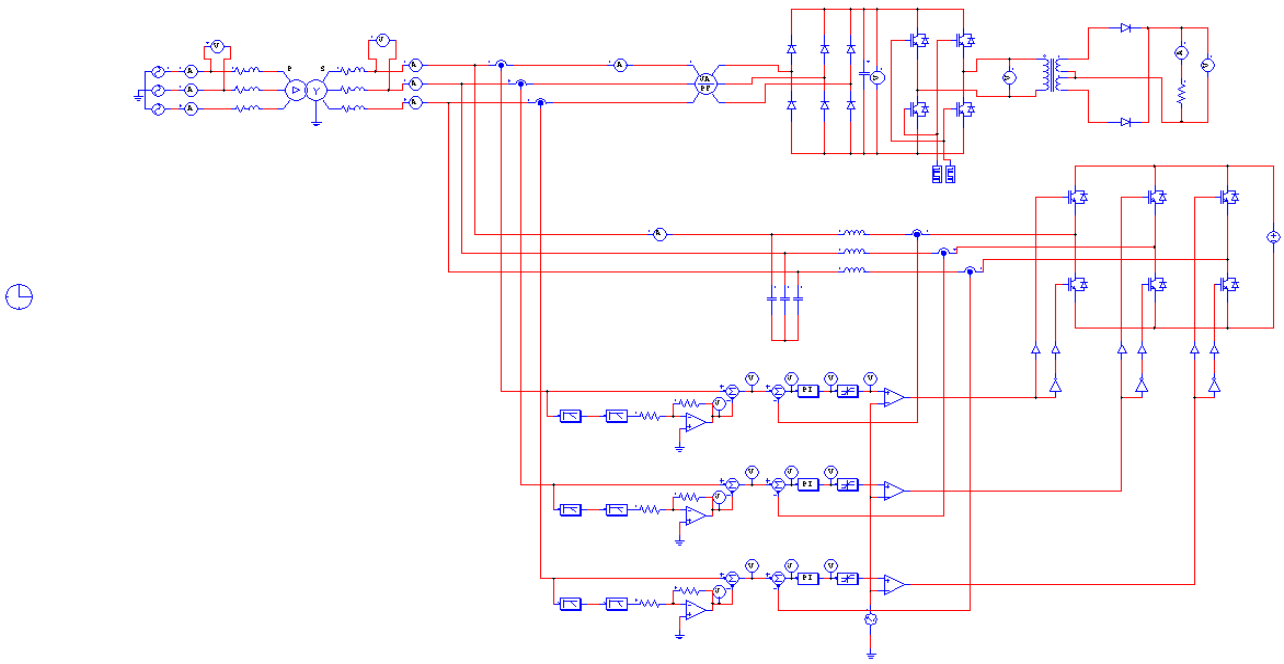

Fig.12. Simulation model of RSW after using propose SAF

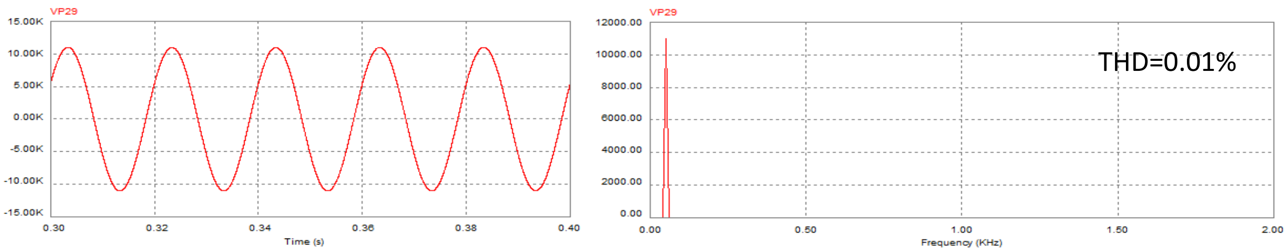

Fig.13. Voltage waveforms and its frequency spectrum at MV side after using SAF

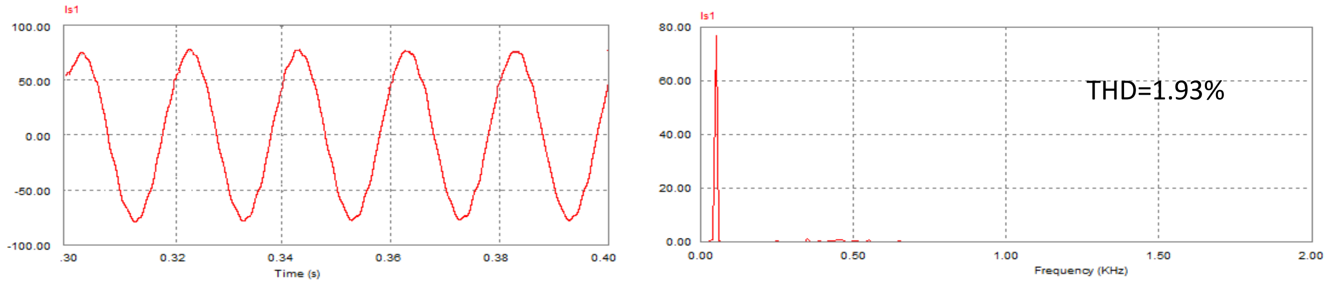

Fig.14. Current waveforms and its frequency spectrum at MV side after using SAF

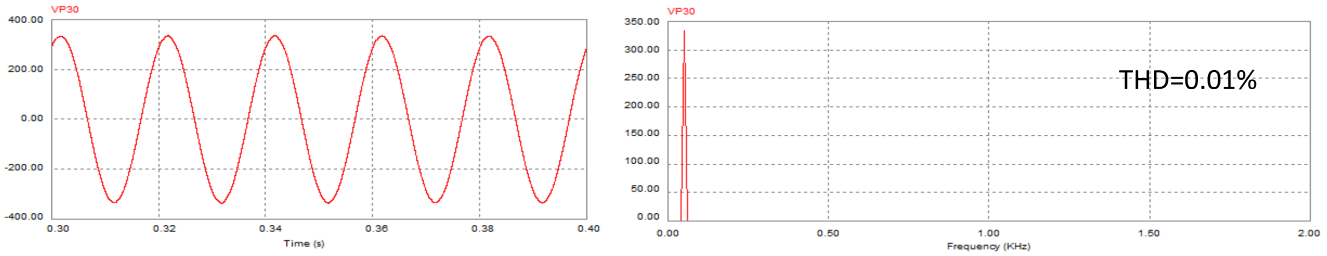

Fig.15. Voltage waveforms and its frequency spectrum at LV side after using SAF

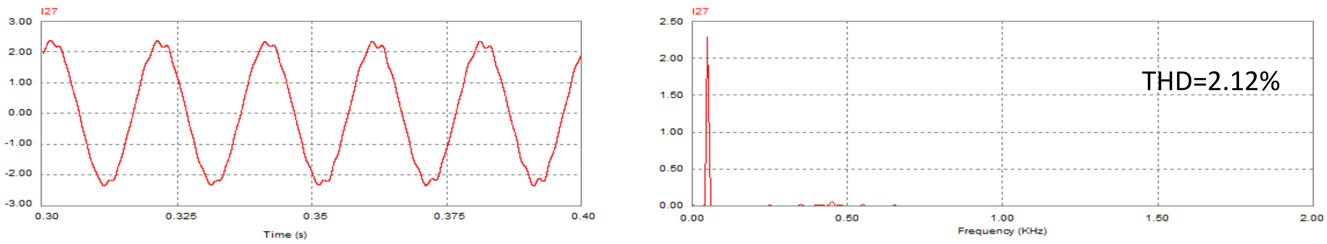

Fig.16. Current waveforms and its frequency spectrum at LV side after using SAF

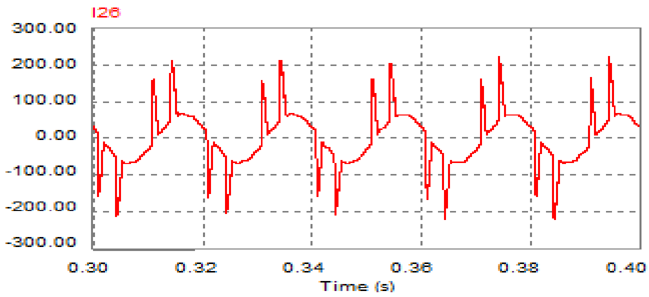

Fig 17. Compensating current of the proposed SAF

6. Comparison between the harmonic results from the RSW and the IEEE 519 limits

Table 3. shows the harmonic results from the RSW before and after filtering compared with the IEEE 519 limits[18]. The SAF reduced the THD of the RSW current at MV side from 84.85% to 1.93% and at LV side from 87.28% to 2.12%. That means the distortions in the waveforms are decreased and the supply current becomes harmonics free.

Table 3. Harmonic results from the RSW before and after filtering compared with the IEEE 519 limits.

Harmonic spectrum	Fund.	5th	7th	9th	11th	13th	17th	19th	23th	25th	THD%
at MV side before filtering %	100	67.82	50.43	6.27	2.63	2.18	1.81	1.45	0.45	0.36	84.85
at MV side after filtering %	100	0.98	0.84	0.56	0.42	0.34	0.31	0.28	0.1	0.08	1.93
at LV side before filtering %	100	25.87	18.32	5.12	4.46	3.32	2.72	2.51	1.98	1.72	87.28
at LV side after filtering %	100	1.24	1.04	0.97	0.89	0.52	0.45	0.31	0.23	0.15	2.12
IEEE %	----		7		3.5		2.5		1		8

7. Conclusion

This paper dealt shunt active filter for installation on a resistance spot welding machine. The total harmonic distortion of the input current of this machine exceeds the limits reported in the IEEE Std. 519-1992. The proposed filter uses a low-pass filter with the PWM carrier strategy to control the current of active filters. This filter could suppress the harmonics to a minimal extent in order and becomes within limits and gives the same result when using band-pass filter to control the current of the filter, with less expensive, mathematically simplest and most common approximation. The proposed method can be used in different applications with only simple modifications. The simulation results using the PSIM software verify the analysis and show the control performance.

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