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Harmonic Analysis of Traction Power Supply Substation Medium Voltage Line

Deepak Shrivastava[1], **Shiv Kumar Tripathi**[2]

PG Scholar, Department of Electrical & Electronics, Corporate Institute of Science &Technology,
Bhopal, India[1]

Asst. Professor, Department of Electrical & Electronics, Corporate Institute of Science &Technology,
Bhopal, India[2]

ABSTRACT: Modern DC electric railway traction powersupply system consists of a twelve-pulse rectifier which willcause 11th and 13th order harmonics to be injected into the powersystem. A shunt active harmonic filter (SAHF) is proposed tomitigate the harmonics at medium voltage (MV) line. SAHFcontrol strategy usually consists of three core elements whichinclude reference current generation, DC-link feedback control,and current control and gate signal generation. This paperproposed a distinct time domain-based control strategy withDC-linked feedback reference current compensation methodwhich has a simple topology, low mathematical complexity, andfast response time. Detailed performance analysis of SAHF iscarried out in the parameter selection process whereby theeffects of each parameter are discussed. The implementation ofSAHF in traction power supply substation (TPSS) is simulated using MATLAB/Simulink.

KEYWORDS: shunt active power filter, voltage source converters, harmonics , High Voltage Direct Current (HVDC), transmission systems,Power quality

I.INTRODUCTION

transportation makes the service convenient, fast and environmentally friendly. However, this also brought a new challenge to the power grid. Especially rapid development in the power electronics technology and the increase in the application of these devices in the railway sector exposed the traction power supply system to a distorted waveform that affects the overall performance of the network due to harmonic currents injected into the system by non-linear loads. This current flow into the surrounding grid through the transmission lines and causes power quality problems that cannot be ignored. It is noteworthy that when there is a resonance into the system, the harmonic current amplified significantly, which in turn disturbs the neighboring lines of communication and the railway signaling system [1]. In addition, it causes overheating, instability of the power capacitors, and brings malfunction of protection devices. Therefore, the harmonic current flow must be assessed accurately in the design and planning stage of the electric traction system [2]. It also needs to be precisely modelled to analyze and assess the harmonic effect on the power-feeding system [3].One such industry is the electric railway industry. Modern electric railways are powered via DC supply so AC to DC converters are required to convert AC supply from utilities to DC supply. The railway system started with the use of steam power whereby, in 1804, the construction of the first full-scale railway steam locomotive by Richard Trevithick was completed in the United Kingdom [1]. Then, in 1881, Werner von Siemens constructed the first electric tram line in Lichterfelde, Berlin, Germany [2]. This marks the start of the electrification of railways. In 1904, DC traction motor powered by transformer and rotary converter started to be utilized on the Seebach-Wettingen line of the Swiss FederalRailways. The development of high-speed railways by the French TGV and the Japanese Shinkansen in the 1980s promoted another round of railway electrification globally [3].Containing thyristor rectifiersused for controlling speed in electric railways, they have anon-linear characteristic which leads to current harmonicdistortion (CHD). Considering system impedance, such CHDleads to harmonic voltage distortion (VHD). From electricgrid viewpoint, the electric railway is a non-linear variableload and is considered as one of the most unfavorable loads[1,2]. In addition to high reactive power consumption, electricrailway injects an enormous amount of harmonic currentwhich is almost equal to 2-3 times of allowable systemharmonic level [3]. Harmonics induce plenty of troublessuch as excess loss in system, unsuitable function of controlsystems and improper trips of relays. In order to compensate reactive power and eliminate harmonics, a proper filter mustbe applied. There are three kinds of filters: passive, activeand hybrid filter which is a combination of active and passivefilters. Each of passive and active filters has its own pros andcons. However, hybrid filters have advantages of both activeand passive filters and on the other hand, few disadvantagesin comparison to these two filters. Hybrid filters havedifferent structures with regard to their connections. Eachof these structures has its own advantages.There are various methods to eliminate harmonics. One ofthe methods is through the use of power harmonic filters. Thefilters can be classified into passive, active, and hybrid filters.This paper will focus on active harmonic filter (AHF) due toits ability to remove all unwanted harmonics present in thesystem which, unlike passive harmonic filters, each filter canonly remove certain targeted harmonics.The basic concept of AHF has first appeared in 1969 asdescribed in [6]. Then, in 1976, the basic design of modernAHF was proposed in [7]. However, it was only until the1990s where high-power and high-switching speed powerelectronics became available and allow the practical usage ofAHF in power systems [8].This paper presents the performance analysis of mediumvoltage SAHF with VSC via parameter testing to determineoptimal SAHF configuration to mitigate harmonics generatedby the electric railway system in Malaysia in compliance withIEEE std. 519-2014. Besides that, a proposed referencecurrent generation method for the SAHF control strategywhich has a simple topology and consumes minimalcomputational power is discussed. Implementation of DC-linkfeedback control to compensate reference current is alsoproposed. The study is in anticipation of the future expansionof the railway system. So, this paper will serve as an importantreference for harmonic mitigation in the near future.

II. METHODOLOGY OF PROPOSED SYSTEM

For mitigating the harmonic distortion passivefiltering is the simplest conventional solution. Themost commonly used passive filter is the singletuned filter. This filter is simple and least expensiveas compared with other means for mitigating theharmonic problems. Low cost is a great benefit of these filters. Thesefilters are always connected in parallel across thenetwork.The model shown in Fig. 1 is a simplified closed-loopmodel of the studied urban DC electric railway TPSS systemin the form of a typical twelve-pulse system. The model isconstructed via MATLAB/Simulink. The system is based ona DC traction railway in Malaysia which operates at 750V DC.The system is supplied with 33kV AC, 50Hz by the tractionpower supply substation (TPSS) provided by the public utilityat the MV side.

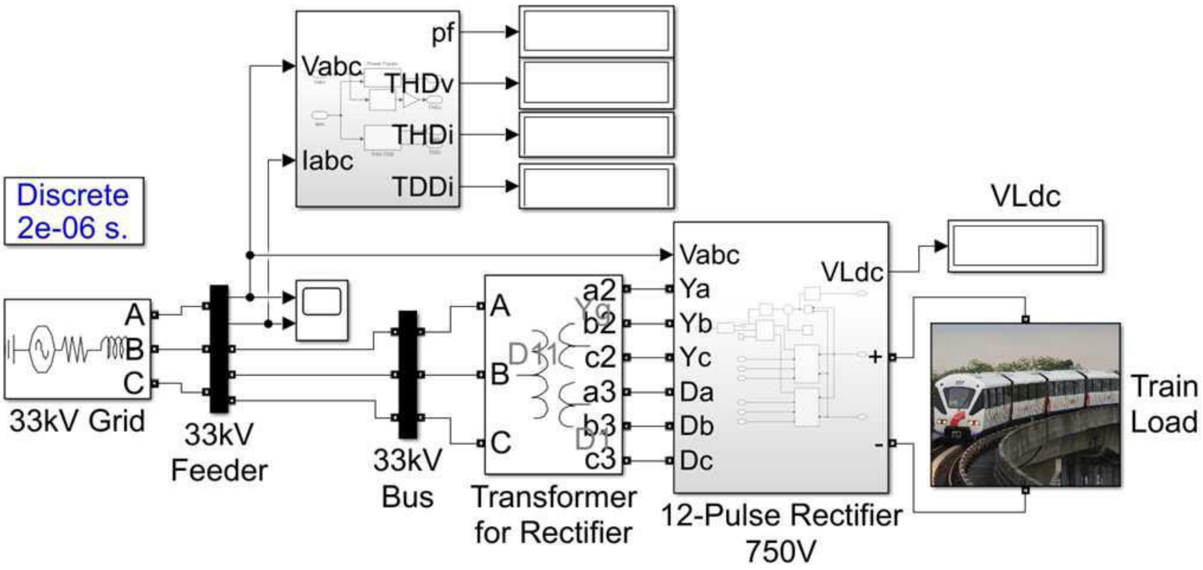


Figure 1: DC electric railway TPSS model

A 3300kVA three-winding rectifier transformer is used to step down the power supply from 33kV AC to 585V AC at the low voltage (LV) side. The transformer consists of one primary winding and two secondary windings which are separately named secondary and tertiary winding. The primary winding is in delta connection which is leading. The secondary winding is in wye connection. The tertiary winding is in delta connection which is lagging.Each of the two three-phase thyristor-based rectifiers isconnected to the secondary and tertiary winding of the rectifiertransformer respectively. Then, the two rectifiers areconnected in parallel. A resistive load, representing the trainload, is connected to the rectifiers.The rectifiers are controlled via the use of a twelve-pulse generator. Due to the varying load conditions, a closed-loopcontrol method is applied to generate a suitable firing anglefor the pulse generator using a PI controller to maintain theload voltage at 750V DC as shown in Fig. 2 with proportional(*Kp*) and integral gain (*Ki*) of 0.3 and 50 respectively. Theoutput saturation has been set to limit the alpha firing angle tobetween 0 to 120.

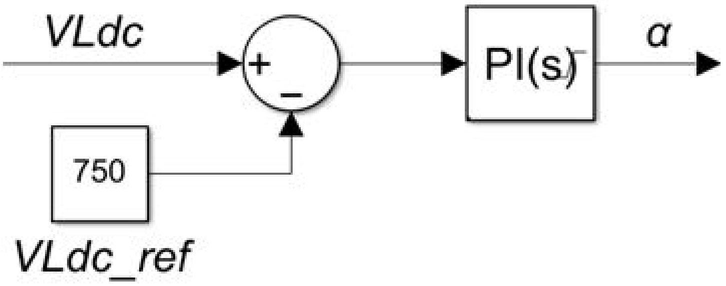


Fig. 2. Closed-loop control model

III. HARMONIC FILTERING

We used in this article passive filters which are aclassic methods for power quality improvement ,consist of series LC tuned for removing a specificharmonic or blocking a bandwidth of severeharmonics of nonlinear loads current.For mitigating the harmonic distortion passivefiltering is the simplest conventional solution. Themost commonly used passive filter is the singletuned filter. This filter is simple and least expensiveas compared with other means for mitigating theharmonic problems [10]. These filters have lowimpedances for the tuned frequencies such as 11thand 13th (used in our application).Low cost is a great benefit of these filters. Thesefilters are always connected in parallel across thenetwork.The harmonic analysis of the railway system modelwithout SAHF is carried out via MATLAB/Simulink FFTanalysis tool. The sampled window size is 10 cycles for a 50Hz power system. It is generally known that the twelve-pulserectifier of the modeled railway system will cause 11th and 13thorder harmonics [13]. Therefore, 11th and 13th order harmonicswill be the main individual harmonics to be mitigated in thispaper. Since harmonic distortions are more prominent in offpeakthan peak load conditions, only off-peak load conditionsupply voltage and current waveform and FFT analysis areshown.These filters wouldnormally be tuned below the respective characteristic frequencies.This is done for the following practical reasons.

- Perfect tuning would attract the dominant harmonics of theneighboring non-linear loads and result in overcurrentcondition in the filter and fail.
- Filter components, in particular, the capacitor C parameterdecreases due to ageing, and the tuning frequency movesupwards and design at or above the tuning frequencywould result in degraded filter performance. With lowerfrequency detuning, the series resonance frequency increasesand shift the minimum impedance point closer tothe harmonic frequency. This increases the effectiveness ofthe filters by suppressing more current harmonics.
- Lower frequency detuning may be necessary to move theparallel resonance frequency away from the dominant harmonicfrequency. Depending on the line impedance parameters,this may be necessary to avoid large overvoltagestresses on the rectifier terminals due to parallel resonanceat the discussed harmonic frequency.

IV. COMPENSATED SHUNT ACTIVE HARMONIC FILTER

The shunt active harmonic filter (AHF) is a device that is connected in parallel to and cancels the reactive and harmonic currents from a nonlinear load. The resulting total current drawn from the ac main i s sinusoidal. Ideally, the APF needs to generate just enough reactive and harmonic current to compensate the nonlinear loads in the line. In an AHF depicted in Fig. I, a current controlled voltage source inverter is used to generate the compensating current (L) and is injected into the utility power source grid. This cancels the harmonic components drawn by the non-linear load and keeps the utility line current (i,) sinusoidal. A method is used for instantaneous current harmonics detection in active power filter is synchronous d-q reference frame theory separating successive harmonic components. SAHF consists of voltage source converter with DC link capacitor which generates compensating current with 180 phase opposition and injects at the Point of Common Coupling (PCC) in the grid, so as to cancel out the current harmonics caused by the non-linear load. SAHF compensate current harmonics by injecting equal-but opposite harmonic compensating current. The components of harmonic currents contained in the load current are cancelled by the effect of the active filter, and the source current remains sinusoidal and in phase with the respective phase to neutral voltage. With an appropriate control scheme, the active power filter can also compensate the load power factor [7].

V. CONTROL STRATEGY OF SAHF

As the most integral component in ensuring optimalperformance of the SAHF, it is important to select the mostsuitable control strategy based on the applications. For thispaper, the SAHF is applied at 33kV MV line. Therefore, thecontrol strategy applied is aimed to reduce the computationalcomplexity and improve response time for harmoniccancellation which will ultimately lower the cost of SAHF.The proposed control strategy is named DC-linkedreference current compensation method. Fig. 4 shows thetopology of the three-phase SAHF with the proposed controlstrategy.A general overview of the control strategy consists of threecore elements which are reference current generation, DC-linkfeedback control, and current control and gate signalgeneration .Lack of any of the coreelements will result in the SAHF not functioning as required.

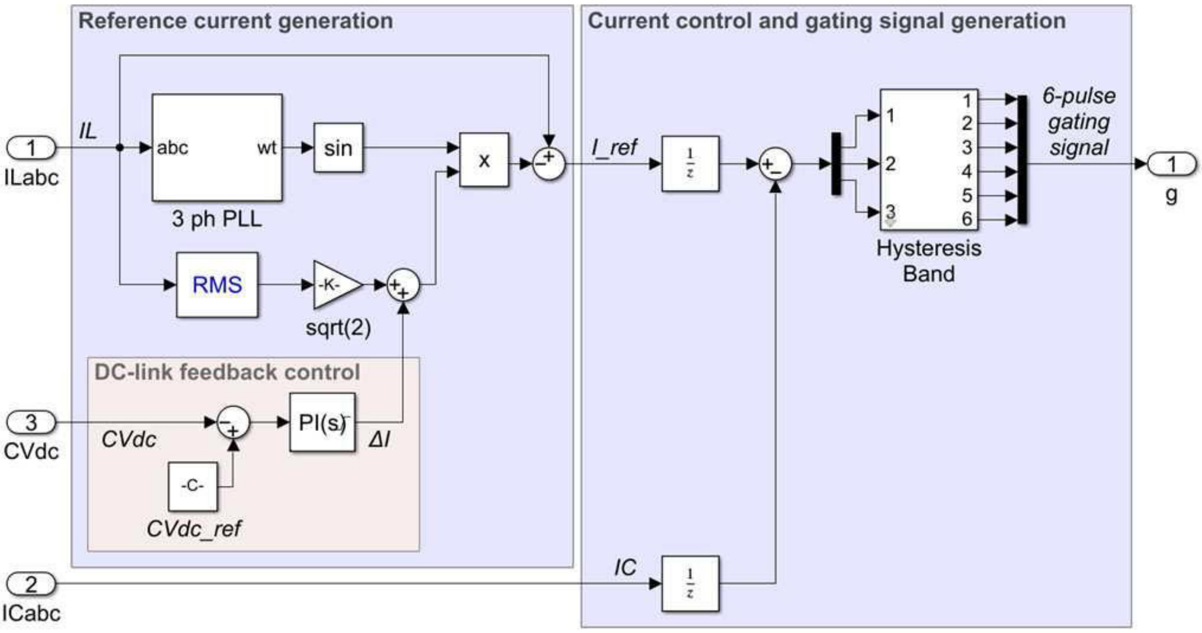


Fig. 3. Proposed DC-linked reference current compensation control model

The reference current generation stage is the mostimportant aspect of the SAHF control algorithm as referencecurrent (I_ref) will directly impact the accuracy of harmoniccancellation. Time domain-based methods are chosen as theyhave a fast response time and uses less computational power.A proposed reference current generation method, named DClinkedpeak compensation control, is implemented due tobeing less mathematically complex which improves theresponse time.When the error signal between I_ref and IC is within thehysteresis band limit, the gating signal will remain unchanged.Inversely, the gating signal will be toggled by the hysteresisswitch each time the error signal exceeded the band limitwhich is either from 1 to 0 or vice versa. As a result, the actualIC generated by SAHF will resemble the I_ref to compensatedistorted load current waveform.

VI. RESULTS AND DISCUSSIONS

By using MATLAB/Simulink, a DC electric railway TPSSwith SAHF model is created to evaluate the performance ofSAHF in mitigating harmonics in loadconditions. DC-linked reference current compensationmethod is implemented as the SAHF control strategy.the effects of increasing the magnitude of theparameters involved on SAHF performance resulted indifferent outcomes. Lf, HBL, Kp, and Ki are not considered inthe performance analysis as Lf and HBL are fixed parameterswhile Kp and Ki are dependent on the filter capacitance. Forfilter capacitance, it has increased the SAHF settling time andreduces Vpp. Besides that, CVdc_ref will vary the SAHF settlingtime, reduces power factor, THDi, TDDi, 11th and 13th order THDi, and increases THDv. Lastly, Irange reduces SAHF settlingtime.

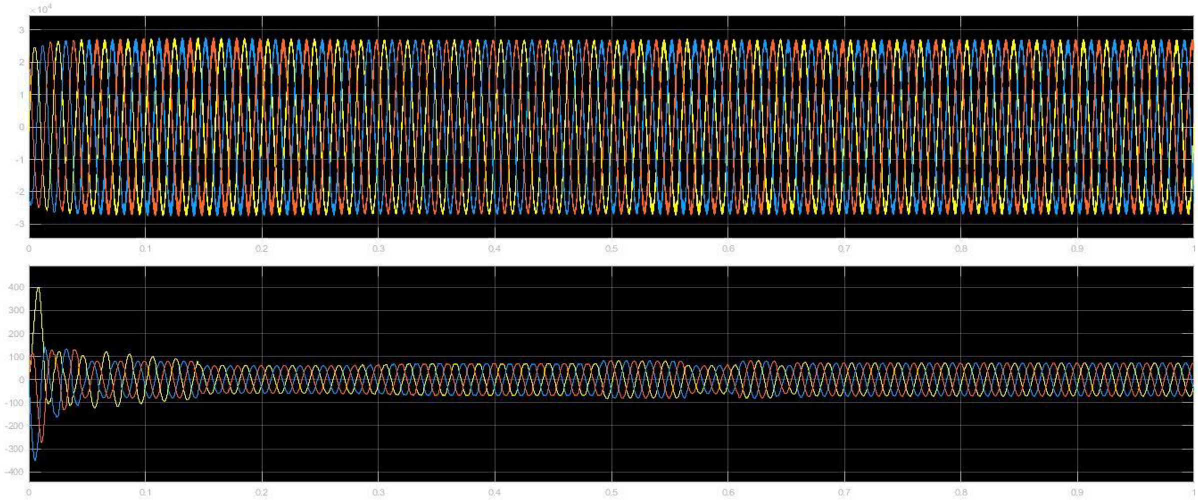
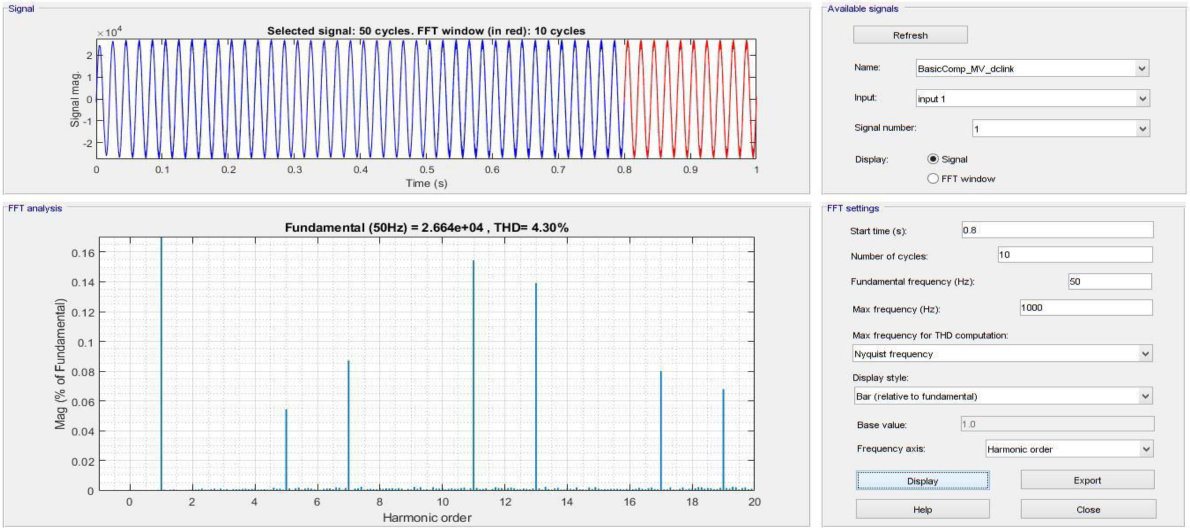


Fig 5Source voltageand Source Current



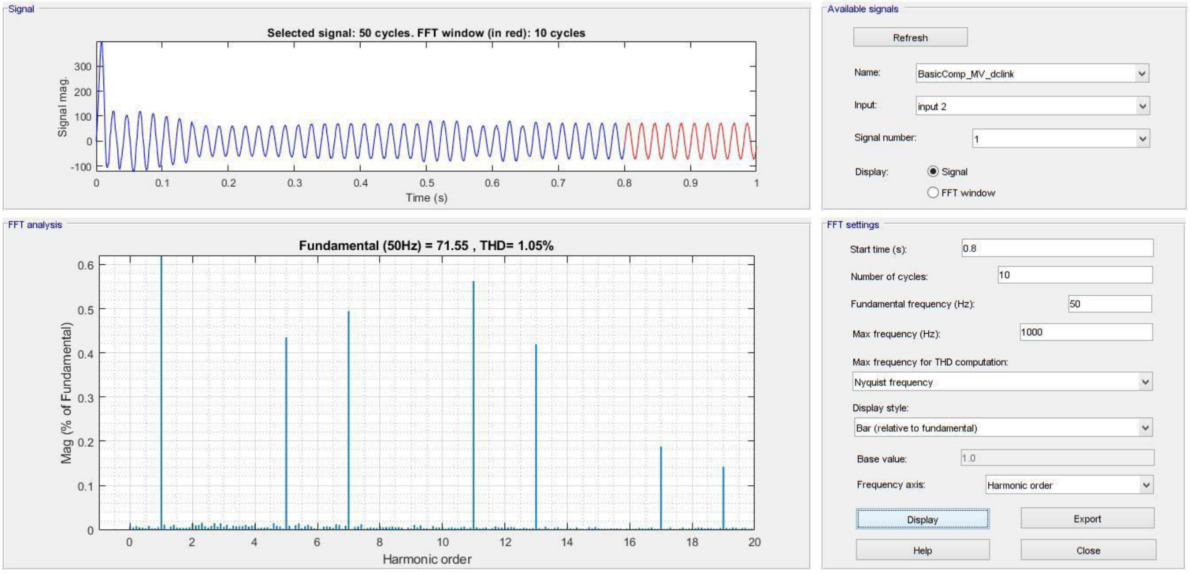
Selected signal: 50 cycles. FFT window (in red): 10 cycles

Fundamental (50Hz) = 2.664e+04 , THD= 4.30%

Name: BasicComp_MV_dclink
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 0.8
Number of cycles: 10
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Fig.6 Harmonic spectrum of the source voltage



Selected signal: 50 cycles. FFT window (in red): 10 cycles

Fundamental (50Hz) = 71.55 , THD= 1.05%

Name: BasicComp_MV_dclink
Input: input 2
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 0.8
Number of cycles: 10
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Fig.7Harmonic spectrum of the source current

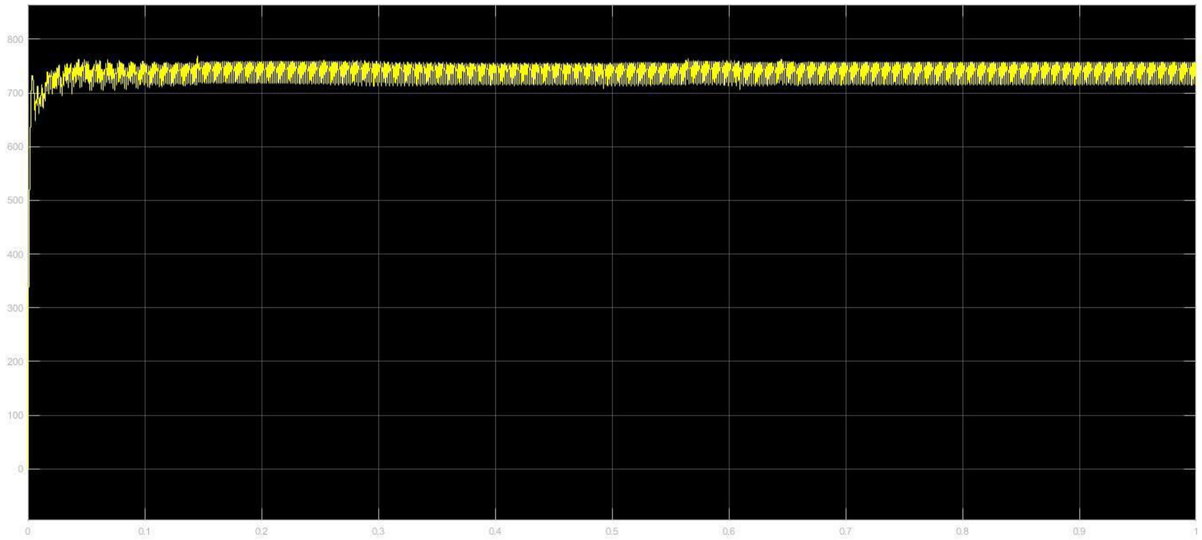


Fig 8Load voltage

VII. CONCLUSION

In summary, performance analysis of SAHF is carried outby evaluating the SAHF performance in mitigating theharmonic distortion present in DC electric railway TPSSsystem at the 33kV MV line. Prior to harmonic mitigation, 11thand 13th order harmonics are the dominant harmonics presentin the affected system. The SAHF control strategy, namedDC-linked reference current compensation method, isproposed which consists of three core elements namely DClinkedpeak compensation control, DC-link feedback control,and hysteresis band control. I_ref is generated in the DClinkedpeak compensation control stage while the hysteresisband control stage will ensure the actual IC generated will besimilar to the I_ref. DC-link feedback control improves SAHFperformance by compensating switching loss. the harmonic analysis resulthas shown that THDv, TDDi, 11th order IHDi, and 13th orderIHDi of TPSS MV line is reduced to levels lower than 4.61%,1.03%, 0.96%, and 0.67% respectively.Therefore, the proposed control strategy is shown to becapable of mitigating harmonics at the 33kV MV line with theadvantage of having a simple topology, minimal mathematicalcomplexity, and fast response time.

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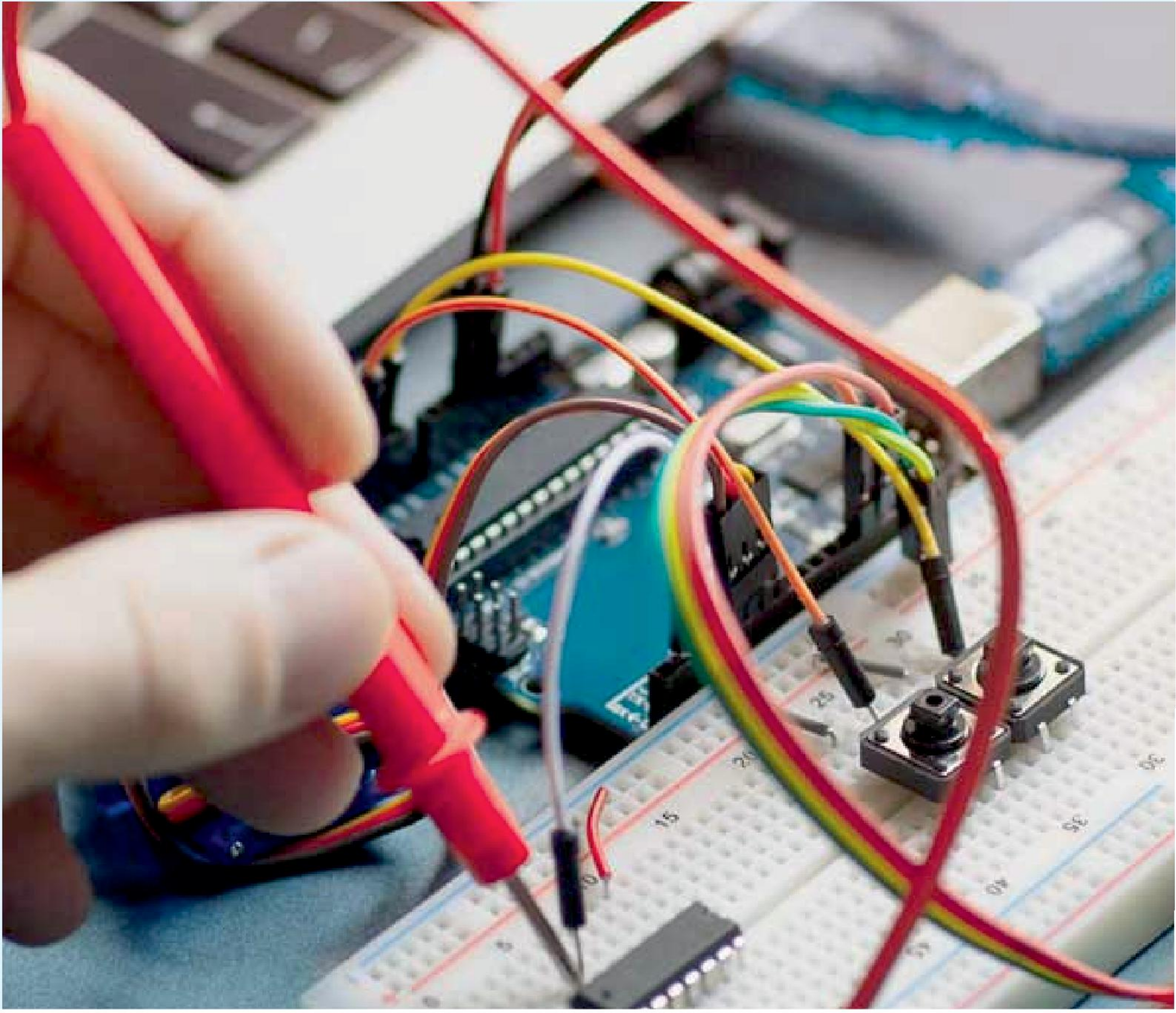

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