Analysis of DC-Linked Reference Current Compensation Control of Shunt Active Harmonic Filter (SAHF) for Traction Applications

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ABSTRACT

Since the advent of AC power systems, issues related to power quality—particularly harmonics—have been observed. Initially, harmonics were not considered a significant concern, as the majority of grid-connected loads were linear in nature. However, with the widespread integration of high-power electronic devices, harmonic distortion has increased substantially. These power electronic devices, typically classified as nonlinear loads, are now commonly used in various sectors as converters and motor drives.

This paper introduces a unique time-domain control approach that incorporates a DC-link-based feedback reference current compensation technique. The proposed method features a simple configuration, low computational complexity, and quick response characteristics. A comprehensive analysis of the Shunt Active Harmonic Filter (SAHF) is presented, focusing on parameter selection and the influence of individual parameters on system performance. The SAHF is implemented and simulated in a traction power supply substation (TPSS) using MATLAB/Simulink. Simulation results demonstrate that the proposed SAHF effectively reduces harmonics within acceptable limits.

Keywords- Harmonic Distortion; power converter; traction power supply substation (TPSS); nonlinear loads; Electric Power Quality (EPQ)

INTRODUCTION

The distribution system is a vital connection between the generation and utilization of electrical power at rated amplitude and frequency, which indicates the Electric Power Quality (EPQ) [1].. Poor power quality sources are raised from two categories: (i) Non-linear loads, electrical components and equipments (ii) Subsystems of transmission and distribution systems. The electric power quality has become an important part of the distribution power system. Harmonics are the primary cause for the poor power quality of the distribution system. The emergence of electricity as the main power source of railway 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 note worthy 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 modeled to analyze and assess the harmonic effect on the power-feeding system.

The electric traction system is the most efficient traction system. It offers several benefits over other systems, including quick start and stop, very efficient, pollution free, easy to handle and easy speed control [2]. The DC electric traction system plays again an important role for domain of transportation because of high efficiency, heavy ridership and fast transportation of series DC motor (high initial torque) , and we note that DC train consumes less energy compared to alternating current (AC) unit for operating same service conditions However, the DC electrified railways cause a lot of problems for the power quality such as injecting harmonics (high THD); reactive power , and low power factor issue [4-5]. In this paper we concentrated on filtering of currents harmonics generated by the DC electric traction units in a railway system by using passive filter which installed on different locations of transformer feeding (before , after). Electrified railway systems (RES) are used widely around the world as a significant means of fright and public transportation. A traction power supply or traction power network is an electricity grid for the supply of electrified railway networks. Rail transit power supply system converts electrical energy in to mechanical energy to drive electric trains, electric multiple unit sand urban trains. The evolution in electrical traction systems has produced a variety of electrification systems inspired to very different principles. Nowadays, it has been an increased concern about the effects of nonlinear loads on the electric power system. The present design trend in electrical load devices is to increase energy efficiency with solid-state electronics. These non-linear loads are any loads which draw current which is not sinusoidal.[6] While nonlinear loads are not new, their increased use means a larger percentage of any power system tends to be nonlinear. One of the major drawbacks of this trend is the harmonics injection to the power system. The effect of harmonics in power system considerably increased due to the use of electronic loads and other high frequency producing devices. With the widespread application of electronics to virtually every electrical load, non-linear loads are also prevalent in commercial and even residential power systems. In this paper we analyze performance of Shunt active harmonics filters and their control topology. Shunt type AHF (SAHF) is proven to be most effective against harmonic currents and it is most commonly used with VSC. VSC is more efficient, lower cost, and smaller than CSC. The overall control strategy consists of three core elements which are reference current generator, DC-link feedback control, and current control and gate signal generator. The generation of reference current can be carried out based on frequency domain, time domain, or soft computing. Among the three methods, the time domain method is faster, less complex, and uses less computing power. Proposed Methodology Performed in Mal-lab Simulink model and verified their result as expected.

Power Quality Problems in Electric Railway

Power quality in a newly constructed electrified railway system is a hot issue. This is because, poor power quality not only causes energy loss within the systems but it could also result in the malfunctioning of the electric traction equipment integrated and connected to the systems. AC electrified railway systems typically show low power quality due to their inherent electrical characteristics. The inductive and the non-linear load characteristic of the locomotives instigate the consumption of a considerable amount of reactive power and the generation of higher harmonic currents. This in turn causes the power factor of the electric power systems delivered to the locomotives will reduce. The power quality problems in the AC electrified railway systems defined to above could have a harmful impact on the railway system as well as on all the other electric equipment connected to them [4]. The railway electrification load is one of the worst kinds of load for an electrical utility to supply. The only load which gives more challenge to the utility is arc furnace load. The railway electrification load is highly intermittent, irregular, low load factor and poor power factor. The railway electrification load creates system voltage and current unbalance, generates harmonics and results in voltage flicker. Because of the above characteristics the railway electrification load generally requires oversized substation facilities. It stresses the electrical utility equipment more and also causes interference with other customer loads and often complaints from the other utility customers, etc. [1]. An electrified railway line resembles a typical power transmission and distribution system. The major difference is that the loads (trains) move and change operation modes frequently. Power demand varies over a wide range and a load may even become a source when regenerative braking is allowed. Other uncertainties are resulted from a number of factors, such as service scheduling, train speed, traffic demands, track layout, traction equipment control and drivers behavior to name a few.

Problem Statement

In a new electrified railway line can happen a power quality problem of huge reactive power consumption, voltage drop, and harmonics because of the load characteristics of the electric traction. The nonlinear load characteristics of locomotive consume large reactive power, produce harmonic voltage and current at the pantograph, as result traction substation delivers insufficient power to the locomotive. Unless remedial action is taken, the result will be deterioration of power quality, not only harmful traction system itself, but also prone to spreading through the supply grid, disturbing other users of power in the same grid. Poor power quality problem can affect safety, reliability and the whole operation of railway system. Since our country is constructing thousands of kilo meters of freight and passenger railway route, studying of the power quality problem is a critical issue. Shunt active filter based on synchronous reference frame theory is preferable in order to compensate the reactive power and harmonics mitigation of the traction power supply.

Proposed System Configuration

Methodology consists of the procedures required to design a SAHF and a DC electric railway TPSS model to test its performance. The first step is to model the DC electric railway TPSS system which is based on an actual system. Harmonic analysis is then carried out to determine the harmonic distortion in the power system caused by the railway system. Subsequently, the SAHF is designed with suitable control strategy to reduce the harmonic distortion to the required limits. The Proposed model shown in Fig.1 is a simplified closed-loop model of the studied urban DC electric railway TPSS System in the form of a typical twelve-pulse system. The model is constructed via MATLAB/Simulink. The system is based on a DC traction railway which operates at 750V DC. The system is supplied with 33kV AC, 50Hz by the traction power supply substation (TPSS) provided by the public utility at the MV side.

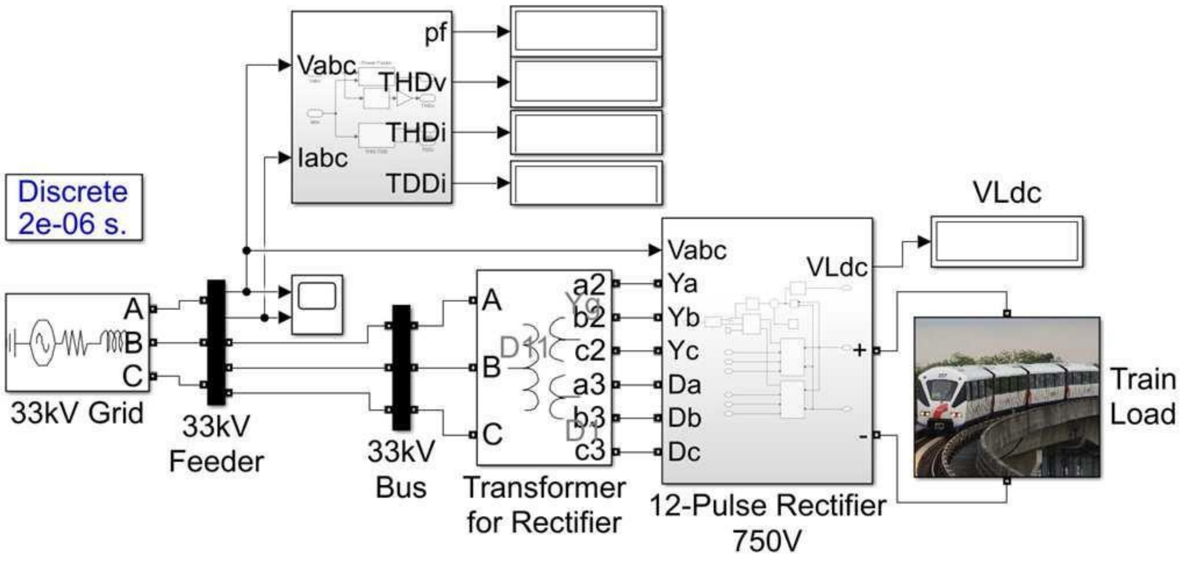


Fig.1. Proposed DC electric railway TPSS model

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 is connected to the secondary and tertiary winding of the rectifier transformer respectively. Then, the two rectifiers are connected in parallel. A resistive load, representing the train load, 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-loop control method is applied to generate a suitable firing angle for the pulse generator using a PI controller to maintain the load voltage at 750V DC with proportional (Kp) and integral gain (Ki) of 0.3 and 50 respectively.

Active Harmonic Filter and Control Strategy

The active harmonic filter (AHF) designed will be in the form of a shunt type AHF (SAHF) with voltage-source converter (VSC) for a three-phase system. Fig.2 shows a simplified diagram of the SAHF design connected to a single or three-phase system**.** The SAHF is connected in parallel to the power system which is experiencing harmonics. It consists of an inductor filter (L_f), DC filter capacitor (C), and full-wave single or three-phase controlled converter bridge whereby IGBTs are commonly used as they are most efficient. I_S, I_L, and I_C are the supply current, distorted load current, and compensating current respectively. The DC filter capacitor functions as an energy-storage component while the controlled rectifier bridge will control the rate of charging and discharging of the capacitor to generate the required IC for harmonic current cancellation.

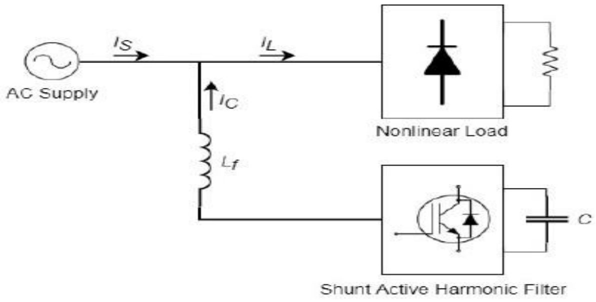


Fig.2.SAHF with single or three-phase system

The most integral component in ensuring optimal performance of the SAHF, it is important to select the most suitable control strategy based on the applications. The SAHF is applied at 33kV MV line. Therefore, the control strategy applied is aimed to reduce the computational complexity and improve response time for harmonic cancellation which will ultimately lower the cost of SAHF. The proposed control strategy is named DC-linked reference current compensation method. Fig. shows the topology of the three-phase SAHF with the proposed control strategy.

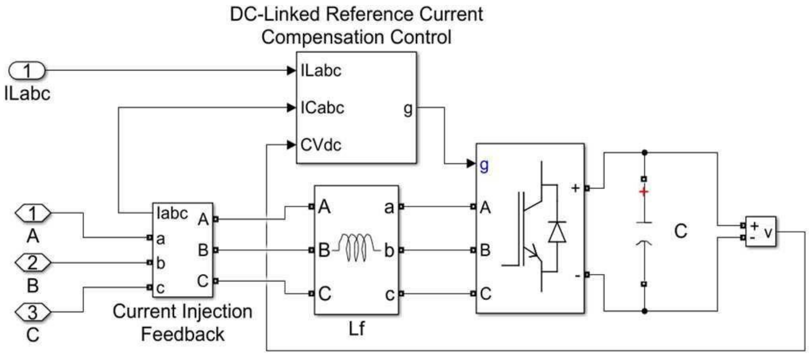


Fig.2Three-phaseSAHFmodel

The control strategy consists of three core elements which are reference current generation, DC-link feedback control, and current control and gate signal generation as shown in Fig.3 Lack of any of the core elements will result in the SAHF not functioning as required.

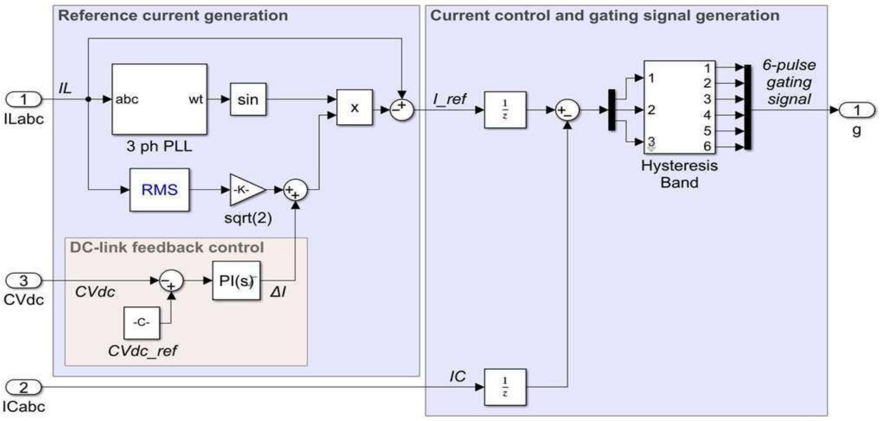


Fig.3ProposedDC-linkedreferencecurrentcompensationcontrolmodel

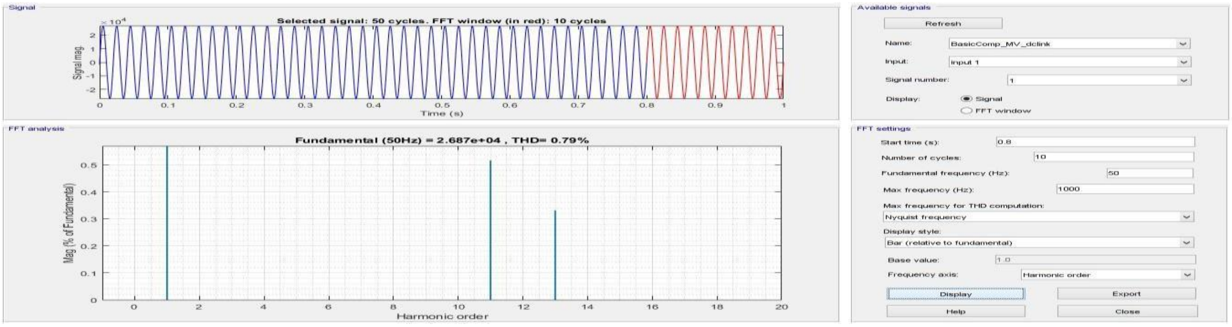
The reference current generation stage is the most important aspect of the SAHF control algorithm as reference current will directly impact the accuracy of harmonic cancellation. Time domain-based methods are chosen as they have a fast response time and uses less computational power.

A proposed reference current generation method, named DC linked peak compensation control, is implemented due to being less mathematically complex which improves the response time. The DC-link feedback control method serves a supplementary yet crucial role in the reference current generation stage to improve the performance of the SAHF. Without the control method, a larger SAHF capacitor is required to maintain the capacitor voltage at a constant level and reduce ripple voltage which drives up the cost and size of SAHF. Besides that, the voltage across the capacitor should be constant in ideal conditions as no real power exchange occurs between the SAHF and the connected power system.

However, in practical situations, power loss still occurs in the form of switching loss due to the filter converter. Therefore,

SIMULATIONRESULTANDDISCUSSION

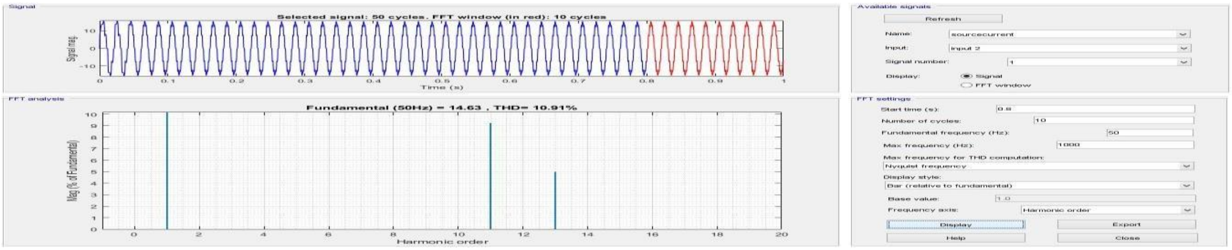
By using MATLAB/Simulink, a DC electric railway TPSS with SAHF model is created to evaluate the performance of SAHF in mitigating harmonics in peak and off-peak load conditions. DC-linked reference current compensation method is implemented as the SAHF control strategy. The simulation is run at discrete time with sample period of 2μs. Harmonic analysis is carried out to observe the resulting harmonic distortion of the affected system after SAHF has been implemented. The parameters involved in the simulation are selected based on requirements which include harmonic distortion levels are to be within the limits. To compare the performance of SAHF with and without DC-link feedback control, the simulation is first carried out without the use of the feedback control method. The harmonic analysis of the railway system model without SAHF is carried out via MATLAB/Simulink FFT analysis tool. The sampled window size is 10cycles for a50 Hz power system. It is generally known that the twelve-pulse rectifier of the modeled rail way system will cause 11th and 13th order harmonics [13]. Therefore, 11th and 13th order harmonics will be the main individual harmonics to be mitigated in this paper. Since harmonic distortions are more prominent in off peak than peak load conditions, only off- peak load condition supply voltage and current waveform and FFT analysis are shown. Fig. 5.1 shows that the supply voltage waveform still retains a pure sinusoidal waveform. This means that there is a low level of harmonics which is indicated by the FFT analysis whereby THD is only 0.79%. The result is much lower than the 5% recommended maximum limit.



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

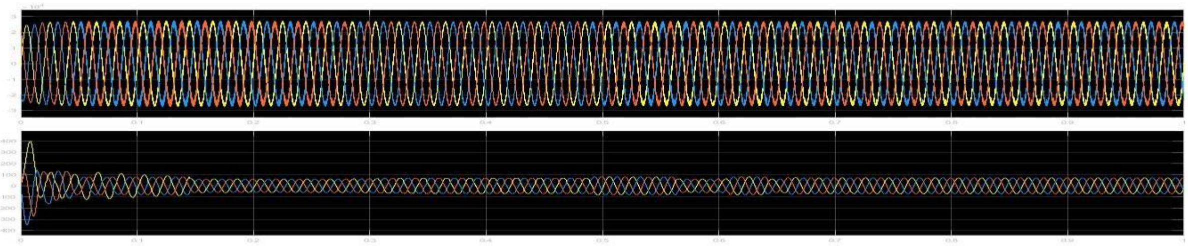
Fig.4 Waveform and FFT analysis of 33Kv supply during off-peak load condition

However, the supply current is highly distorted for off-peak load condition as shown in Fig.4 FFT analysis shows that there is a high level of 11th and 13th order THD i which is 9.23% and 4.98%. So, the 11th and 13th order THD i has exceeded the 2% limit.



Name: sourcecurrent
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.5Waveform and FFT analysis of 33kV supply current during off-peak load condition



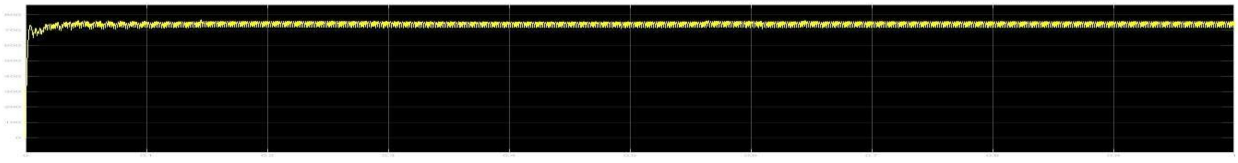
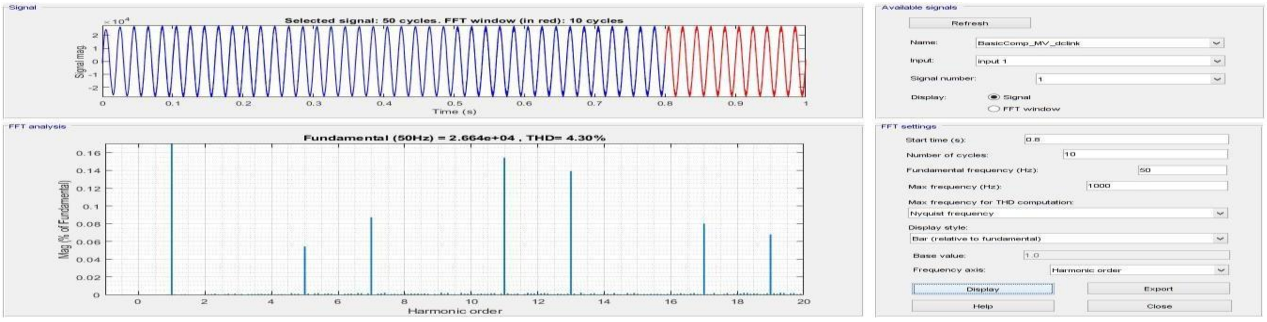


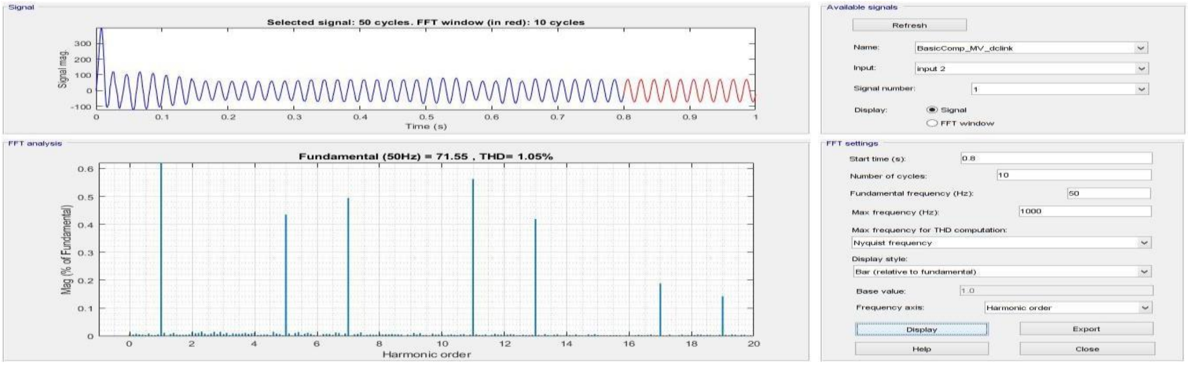
Fig.7 Wave form of Load Voltage



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

FFT settings
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.8 Harmonic spectrum of the source voltage



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

FFT settings
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.9 Harmonic spectrum of the source current

the supply voltage in off-peak load condition has a THDv of 4.61% which is also lower than the 5% limit. 11th and 13th order THD i for off-peak load condition is 0.96% and 0.67% respectively as shown in Fig. overall improvement in terms of harmonic current reduction after SAHF is implemented in the affected system.

CONCLUSION

It clearly visible from the FFT analysis of the MATLAB/SIMULINK model of the circuit with and without filter that the harmonic component present in the source is compensated with use of filter. performance analysis of SAHF is carried out by evaluating the SAHF performance in mitigating the harmonic distortion present in DC electric railway TPSS system at the 33kV MV line. Prior to harmonic mitigation, 11^{th} and 13th order harmonics are the dominant harmonics present in the affected system. The SAHF control strategy, named DC-linked reference current compensation method, is proposed which consists of three core elements namely DC linked peak compensation control, DC-link feedback control, and hysteresis band control. I_ref is generated in the DC linked peak compensation control stage while the hysteresis band control stage will ensure the actual IC generated will be similar to the I_ref. DC-link feedback control improves SAHF performance by compensating switching loss. the harmonic analysis result has shown that THDv, TDDi, 11th order IHDi, and 13th order IHDi 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 be capable of mitigating harmonics at the 33kV MV line with the advantage of having a simple topology, minimal mathematical complexity, and fast response time. Safe operation of SAPF is also studied in order to develop a protection system against transient conditions such as; (i) Overload, (b) Fault and (c) Inrush current. The proposed protection system is based on digital current limiter to avoid switches damage in addition to implementing second harmonic ratio to make a discrimination between fault and inrush current.

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